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Reservoir Connectivity and Stimulated Gas Flow in Tight Sands

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Note: Due to file size, the entire Final report can be found at:

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Abstract

This was a comprehensive research project consisting of multiple tasks in geology, geophysics, petroleum engineering and rock mechanics, all designed to explore the relationships between the architecture of tight gas reservoirs in the Piceance Basin, Colorado, and their fluid flow characteristics. The overall project goal was to improve the predictability in exploration for and the completion and production of these reservoirs. The culture of open exchange of data, ideas and insights between several research universities and organizations and the many companies operating in the region played a huge role in the overall success of the project.

More than 6000 well logs, several 2-D seismic lines, and 3-D seismic data cubes for the Mamm Creek and Rulison fields were made available to the investigators on this team, from a combination of donated industrial data bases and public resources. Given the unique situation of having a number of huge natural gas fields, surrounded on all sides by excellent outcrops of reservoir-equivalent strata, the team also made sure that all relevant outcrop information was integrated into the project. What follows is an abstract of selected findings of the eight technical research tasks of the project.

Task 4 provided data and analysis of the structural and stratigraphic controls for static reservoir models for the Mamm Creek Field, specifically, yet the data that were collected and analyzed are of equivalent value also to most other gas fields basin-wide. Outcrop-to-subsurface correlation proved to be a particularly powerful approach to document the size, shape and connectivity of key gas-bearing sandstones in the Williams Fork Formation, the key gas-bearing interval in the basin. This knowledge about sandstone body characteristics was then applied in the modeling of reservoir sandstone bodies as documented in a 3D seismic data cube and logs for parts of the Mamm Creek gas field.

One subtask focused on parameterizing sandstone body architecture, geometries and dimensions from outcrops and closely spaced coal-mine data, within the stratigraphic units that are gas productive in the Mamm Creek Field. Linking these data to the Mamm Creek reservoir models made it clear that gas production from these sandstones is sensitive to net-to-gross ratios and the genetic types and dimensions of the component sandstone bodies. A related and quite fundamental discovery was that most of the gas-bearing fluvial sandstone bodies in this field are smaller than the distance between wells drilled at 10 acres spacing. Thus, how they are distributed and whether or not multiple sandstone bodies are connected are crucial to the optimal development of the field.

Research under Task 4 also clearly documented that diagenetic cements play a significant role as flow barriers within sandstone bodies. Reservoir connectivity, therefore, is not just an issue of overall sandstone body sizes, geometries and distributions, but also affected by internal flow baffles and barriers. Detailed facies analysis of all depositional systems in the stratigraphic interval just below the Williams Fork Formation, the Rollins Sandstone, further amplified the diversity – yet order – to the architectural design of the gas bearing sandstones.

Task 5 explored the larger scales of architecture, at the scale of the basin rather than the scale of the reservoir. The largest scale explored was that of the formation of the entire paleogeography of the region at the time of deposition of these gas-bearing strata, at about 80 to 70 million years ago. Subduction of a (now entirely consumed) oceanic plate, the Farallon plate, pulled the western margin of North America down at the time, creating a 1000-mile-wide seaway which connected the Gulf of Mexico to the Arctic Ocean. The Piceance Basin today occupies a location just west of the western shoreline of this ocean, where sediments were deposited in deltas, related shorelines and river systems draining mountains farther west (in today's central Utah).

The structural deformation of the region, both before and after the deposition of these sediments, is equally important to the understanding of today's hydrocarbon distribution because it is the vertical movement of the basin over time and the changing temperatures within the basin sediments that determine which organic 'source rocks' were cooked to produce gas, when they were so cooked, and how and when they migrated to the gas-bearing intervals from where we produce them today.

Several reports prepared as part of this very comprehensive Task 5 were built on the huge digital well log data set that the industrial partners in this research program provided. Very few research teams have been fortunate enough to get access to this kind of data for research because most basins do not have that degree of well control. It is even more exceptional that all companies operating in a basin are willing to cooperate so intimately within the framework of a public-domain research project like this. These comprehensive stratigraphic studies document the basin-specific distribution of reservoirs, seals, and potential migration pathways. They also provide profound new insights into gas charge distribution, role of stratigraphic as well as structural traps, and the timing of gas generation from the major source rocks (mostly coals just above the Rollins Sandstone). The studies indicate that stratigraphic trapping may play a role in the gas distribution, in addition to the previous conventional thinking that pressure gradients alone provided the dominant control on gas distribution. Recognition of potential new stratigraphic gas traps would further enhance the predictability (and hence cost effectiveness) of basin gas production, above and beyond what we are already learning from reservoir connectivity analysis; as discussed in Task 4.

Task 6 was built on the geological reservoir characterization studies in Tasks 4 and 5 but focused on the dynamic models to properly understand flow connectivity in a portion of the Mamm Creek Field. Gas and other fluids drain through a reservoir during production both via connected sandstone bodies as well as through natural and induced fractures. For most unconventional oil and gas reservoirs, these fracture pathways are keys to optimal reservoir production. The effectiveness of such fractures in conducting fluids from reservoir to well bore also changes over time during field production as pressures change and fractures 'evolve'.

Research performed under this task demonstrates how an integrated approach leads to more realistic 3D geologic and dynamic models that are consistent with static data and historical performance. Such models are useful for estimating the impact of complex

sandstone connectivity on early and long-time performance including well interference, long-term recovery and optimal spacing. When the dynamic (flow) simulation runs for the Mamm Creek Field were validated against historical production data, and tied back to the static models of sandstone body distribution, it was found that the best match was obtained by considering only clean sandstones in depositional systems such as point bars, channel fills and marine sand bodies as pay.

Task 7 was designed to help move reservoir connectivity analysis beyond the empirical and towards a predictive science based on the mechanics of failure in rocks subject to stress. Predicting failure, and the geometry of resulting fractures, is greatly complicated by the fact that real rocks have very heterogeneous composition in terms of mineral grains, cement bonding strength and size and shape of connecting pores. To approximate these complexities, we chose discrete element models (DEMs) for the numerical modeling of such rocks because these codes are designed to handle complex mechanisms, material heterogeneity and failure events at a range of scales. The models now in place as a result of this RPSEA project do allow prediction of the actual mechanical conditions for crack initiation, the effects of varying volumes of weak vs. strong rock layers, confining pressures, porosity of different beds, and bedding geometry.

Included in this comprehensive study of tight gas sandstone reservoirs in the Piceance Basin are four geophysical studies built around an evaluation of vertical seismic profiling for improved reservoir imaging (Task 8), improved accuracy in locating microseismic events (Task 9), understanding the fundamental properties of the self potential field in basin-center gas accumulations (Task 10), and the advancement of seismic shear wave anisotropy analysis to characterize fracture orientation and possibly other anisotropic reservoir properties.

Task 8 addressed 3-D VSP (vertical seismic profiling) using shear waves, and found that this tool offers significant data improvements compared to recording by means of surface geophones. These advantages include: 1) improved image quality from VSP records because of their broader bandwidth and the low noise environment as compared to surface seismic recordings; 2) the depth migrated images tie better with the well logs; 3) the VSP images discern more subtle stratigraphic features, and 4) there is better imaging of structural features, especially faults, which were previously unnoticed on surface seismic data, and 5) differences in reflection amplitudes between sets of split shear waves appear to indicate fractured zones.

Task 9 addressed the use of microseismic tools to locate seismic events during fracturing operations because this approach has become ubiquitous, yet rarely critically examined from geophysical or geological perspectives. A critical geophysical issue was addressed in this study, in which the investigator developed a new approach to determine the precise location of each microseismic event (its 'hypocenter'). Traditionally, people pick P and S wave arrival times at multiple receivers and then triangulate to determine the location of the event's hypocenter. The data is usually quite noisy, however, so hypocenter locations become prone to substantial errors. Instead, the new method developed in this study is based on reconstructing the entire wave field as seen from sets of receivers sensing waves arriving from different directions.

What still remains very much an open question, however, is the determination of what exactly the seismic event represents. Does it truly record the location of a fracture tip or does it represent a seismic shock wave associated with stress release that did not necessarily result in an open fracture?

Task 10 reexamines the oldest of well logging tools, the SP (self potential) tool, because of the curious observation that there is a distinct SP deflection at the abrupt top of overpressure in the gas column and that this signal commonly goes away after several years of gas production and pressure relief. This change is found to be the consequence of a change in the streaming potential (the part of the SP signal that records current related to fluid movement from the rocks to/from the well bore) as the pressure differential across the stratigraphic seal on top of the gas column decreases during production.

Task 11 contributed in a very significant ways to this RPSEA project by making several new advances in processing methods for more effective use of shear waves in detecting reservoir anisotropy. In terms of the role of anisotropy itself, at the 'first order' it is a powerful tool to analyze fracture orientations and therefore of great practical value in reservoir development design. Yet, other attributes of reservoirs, many of which relate to their internal sedimentary and structural properties, also impart anisotropy. The growing use of this technology, therefore, opens up even newer vistas for the use of this technology in reservoir characterization.

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