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The Valle Morado Structure in Northwest Argentina: Kinematic Evolution and Fracture Prediction Inferred from 3-D Seismic Data

INTRODUCTION

The Valle Morado structure, located in NW Argentina near the Bolivian border, is an approximately 7 km long and 4 km wide anticline that trends NNE-SSW. The anticline, cut by a number of faults, was developed during the Andean orogeny and involves more than 6 km of sediments including a Paleozoic basement, and a Cretaceous-Cenozoic cover up to present day sediments. This structure is located between two areas with different stratigraphy and Andean structural styles: the E-vergent, thin-skinned Subandean Ranges to the north, and the E-W-vergent, thick-skinned Santa Bárbara System to the south (e.g., Mingramm et al., 1979; Allmendinger et al., 1983; Jordan et al., 1983; Allmendinger & Gubbels, 1996; Kley & Monaldi, 1998; Kley et al., 1999; Seggiaro & Hongn, 1999). The transition between both belts is interfered by an oblique-trending, aborted Cretaceous rift known as Lomas de Olmedo Trough.

The main reservoir within the Valle Morado structure is a carbonate unit that has shown proven gas bearing on test. In addition, other stratigraphic units have been identified as possible hydrocarbon bearing zones (secondary reservoirs).

A 3-D seismic survey across the Valle Morado structure, together with the application of a number of different analytical techniques allow us to define the geometry of the anticline, validate the interpretation, and to propose a kinematic model for the structural evolution. This information is used to decipher the structural style of the Valle Morado structure located between a thin-skinned and a thick-skinned belt and to predict the orientation, distribution and density of the reservoir-scale fracture system that formed due to folding. A good knowledge of the geometry and kinematics of the anticline is essential to perform volumetric estimations of the reservoir, whereas understanding the sub-seismic resolution fracture network has a direct impact on the development planning of the hydrocarbon field because production may strongly depend on the permeability anisotropy created by fractures.

STRUCTURAL INTERPRETATION OF THE VALLE MORADO STRUCTURE

The Valle Morado structure is a rounded, slightly asymmetrical anticline with a sub-vertical axial plane that has a fold culmination close to its southern termination. The fold axis plunge and the fold limb dip vary depending on the stratigraphic units considered as bedding orientations change across angular unconformities. North of the culmination the fold axis plunges gently to the NNE, whereas south of the culmination it is sub-horizontal or plunges gently southwards. In the southernmost part of the study area, beds dip gently northwards. The western anticline limb dips moderately to the WNW, whereas the eastern anticline limb dips moderately eastwards.

The beds involved in the Valle Morado structure are cut and offset by a number of reverse faults, most of which are located in the anticline limbs. They have listric geometries and their traces are sub-parallel to the anticline axis except for the southern portion of the anticline, where the faults located in the eastern fold limb bend to a NE-SW direction. The major faults cut through the whole stratigraphic succession, from the Paleozoic basement to the Cenozoic units. In general, the faults developed in the western limb of the anticline dip to ESE (hinterland-directed reverse faults), whereas the faults developed in the eastern limb of the anticline dip westwards (foreland-directed reverse faults). Both fault systems seem to control the large-scale structural framework. Thus, transverse sections across the structure illustrate a pop up formed by these two fault systems that branch at depth within the Paleozoic basement and become a single reverse fault system that dips moderately westwards. The pop-up structure is slightly asymmetrical because of the different dips of the anticline limbs and because the accumulated displacement along the eastern fault system is greater than the displacement involved in the western fault system. The displacement along both fault systems decrease from the anticline culmination to the north, so that the maximum structural relief of the pop up with respect to a regional datum also decreases northwards.

CROSS SECTION BALANCING AND RESTORATION

A transverse section across the structure was balanced and restored to a stage before the main Andean contractional deformation. Assuming that the restoration algorithms employed are valid and the results obtained are correct, sudden and important thickness variations of the Pirgüa Subgroup appear to be related to the eastern fault system. On the contrary, there are no thickness variations of this stratigraphic sequence associated with the western fault system. After the rifting event and before the Andean contraction, the eastern faults were almost planar surfaces dipping moderately westwards. It is likely that they curved at deep structural levels. The western faults generated as slightly listric surfaces with steeper dips at the upper levels decreasing to shallower dips to the ESE at the base of the pop up. The partial restoration to the pre-inversion stage also shows stratigraphic units truncated below the Lumbrera Formation, which is sub-horizontal and its base corresponds to an angular unconformity.

The shortening responsible for the formation of the whole structure during the inversion stage is 3.3 km, which is about 28 %. This amount of shortening is within the range of Andean shortening estimated for surrounding areas using regional-scale cross sections; it is slightly higher than the 14-20-25 % shortening estimated for the Santa Bárbara System south of the study area (Grier et al., 1991; Kley et al., 1996; Cristallini et al., 1998) and much lesser than the 42-56 % shortening estimated for the Subandean Ranges north of the study area (e.g., Dunn et al., 1995; Kley et al., 1996).

KINEMATIC EVOLUTION AND TIMING

The geometry of the main faults, their location within the anticline, their disposition parallel to the anticline axis except for the southernmost sector, and their reverse sense of movement suggest that the anticline and these two sets of faults are genetically related.

The Pirgüa Subgroup is thicker in the hanging wall than in the footwall of the eastern faults. This geometry, indicative of growth normal faulting, resulted from deposition within semi-grabens bounded eastwards by extensional faults dipping to the WNW (to the NW in the southern portion of the study area). Therefore, all or part of the Pirgüa Subgroup is a thick syn-rift sequence coeval with movement along the eastern fault system. The Cretaceous age of the Pirgüa Subgroup allows us to establish the timing of the main extensional event in this region. No evidence of thickness variations of the Pirgüa Subgroup, which would indicate syn-rift deposition, appears in the hanging wall and foot wall of the western fault system. The thickness and geometry of the stratigraphic succession overlying the Pirgüa Subgroup suggest that its deposition was controlled to a certain extent by some faults of the eastern system. Beds truncated against the base of the Lumbrera Formation may indicate that some extensional faults were active before deposition of this stratigraphic unit during the Eocene. At regional scale, the Balbuena and Santa Bárbara Subgroups have been interpreted as a post-rift sequence related to thermal subsidence.

The present-day cross sections show reverse senses of movement along the Cretaceous extensional faults described above. The occurrence of internal angular unconformities caused different amounts of reverse offset for different stratigraphic units along the same fault. This reverse movement induced basin inversion. Tectonic inversion also led to folding, and it is likely that reverse reactivation of previous extensional faults and folding were coeval with the development of the western fault system resulting in the present day pop-up structure. In the northern part of the study area, the anticline and main bounding faults are sub-perpendicular to the regional vector of Andean tectonic transport indicating that these structures were formed by almost pure contraction. In the south part of the anticline, where the major eastern faults turn to a NE-SW trend, the faults are oblique with respect to the regional vector of tectonic transport suggesting a component of transpression. It is likely that previous extensional faults were reactivated as dextral-reverse slip faults in the south part of the anticline. The angular relationships between the faults and the Andean contractional vector influenced the geometry of the Valle Morado structure resulting in a dome. Thus, the maximum structural relief of the anticline is located where the eastern faults change strike from NNE-SSW to NE-SW.

The structures responsible for basin inversion during the Andean orogeny (reactivated faults, newly formed faults and folds) affect all the stratigraphic units involved in the Valle Morado structure indicating that this deformation lasted until recent times. Unfortunately, the resolution at the edges of the 3-D seismic volume is not good enough to determine whether thickness variations due to fold/fault growth occur in the synclines adjacent to the anticline. This prevents us from determining the presence of syn-tectonic sediments and establishing accurately the timing of the main inversion pulse.

THE VALLE MORADO STRUCTURE IN THE CONTEXT OF THE SURROUNDING BELTS

The interpretation of the Valle Morado structure supplies new data to place it in the context of the surrounding fold-and-fault belts: the Subandean Ranges and the Santa Bárbara System. The structural style and stratigraphy of the Valle Morado structure fit better with the thick-skinned Santa Bárbara System rather than with the thin-skinned Subandean Ranges because of four main reasons. 1) The Valle Morado pop-up structure, formed by eastward- and westward-dipping faults and an approximately upright anticline, is consistent with the structures observed in the Santa Bárbara System, but it is not with those observed in the Subandean Ranges that mainly consist of eastward-dipping faults and eastward-verging folds. 2) The Valle Morado structure includes faults that penetrate deep into the Paleozoic basement similar to those observed in the Santa Bárbara System. This point on its own is not conclusive because the Subandean Ranges thrusts sole out into a basal detachment located within the Paleozoic succession. 3) The amount of shortening that caused the Valle Morado structure is in agreement with the shortening estimated for the Santa Bárbara System, but it is too low when compared with the shortening estimated for the Subandean Ranges. 4) The Valle Morado structure involves Paleozoic, Mesozoic and Cenozoic sequences similar to those observed in the Santa Bárbara System, whereas the Subandean Ranges involve Tertiary rocks above a Paleozoic sequence.

QUALITATIVE FRACTURE PREDICTION USING CURVATURE ANALYSIS

The geological interpretation of the Yacoraite and Lumbrera Formations within the seismic volume were used to perform curvature calculations because these stratigraphic units are the primary reservoir and the uppermost reservoir seal respectively. Curvature was calculated from maps with various grid sizes at various grid step sizes taking into account the dimensions of the Valle Morado structure. The 300 m grid maps were taken as the most reliable values since the 200 m grid size might reflect the effects of random seismic noise. Finally, the orientation of curvature-based open fractures was compared with that of the open fractures interpreted from the UBI data along the well.

The absolute maximum curvature map shows a strip with high values along the anticline axis which bifurcates to the south. Both the eastern and western branches of the high values of absolute maximum curvature coincide with faults and related minor folds. South of the VM.x-1001 well, the absolute maximum curvature increases substantially following approximately the NE-SW trend of the eastern fault system. High values of absolute maximum curvature along the anticline axis bounded by low curvature areas, together with high values of the curvature ratio along the anticline axis bounded by areas with low curvature ratios, suggest that the fold is approximately cylindrical north of the bifurcation point between the two branches. South of the bifurcation point between the two branches, low values of the absolute maximum curvature and curvature ratios suggest a domal shape. The areas of high absolute maximum curvature and curvature ratio are more suitable for prediction of open fracture trends and provide the highest chance of encountering open fractures.

The well was drilled in an area of low values of absolute maximum curvature and curvature ratio with respect to the Yacoraite Formation, and intermediate values of absolute maximum curvature and curvature ratio with respect to the Lumbrera Formation. This is due to the occurrence of an angular unconformity between both stratigraphic units at this location. In general, some predicted open fractures follow the anticline trend, however, deviations from this trend are common. The direction of open fractures interpreted from the UBI log collected along VM.x-1001 well (Reding, 1999) show a general agreement with the direction of open fractures predicted using curvature around the subsurface location of the VM.x-1001 well in both the Yacoraite Formation and the Lumbrera Formation.

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