Chapter 5: Analysis of the Structural Style and Fracture Distribution of the Ajdagh Anticline in Southern Kurdistan, Iraq
A model for fractured Carbonate Reservoirs

Notes for slides:

Slide 1: This work is the results of field visits to Kurdistan from 2009 – 2011

Slide 2: The Zagros Mountains are the result of a contractional event associated with the transpressional (left-lateral) collision of Eurasia with the Arabian Plate. The study area is located in southern Kurdistan close to the Iranian border. At this location the Zagros Mountains swing toward the hinterland (NE), most likely as a response to a basement low that forms along the trend of the Zagros Mountains to form the southern margin of the Kirkuk Embayment referred to as the Sirwan trough. The convergence of the Eurasian Plate with the Arabian Plate formed the Zagros Mountains. The convergence vector is not pure contraction but is sinistral transpressive. Evidence of the nature of the transpression has not been directly observed in the field but interpretations of structural style generally acknowledges the existence of this sense of convergence

Slide 3: View of a large structure showing the general structural style of the folds. The folds are interpreted to be primarily detachment folds that formed as a result of differential slip on a deeper, as yet undefined, organic rich section. There are numerous possible detaching horizons that range in age from Cambrian to Tertiary. Depending upon the geographic location and geologic time these detachments will be active. In Iran the basal detachment is considered to be Cambrian Salt horizons. In the Kurdish Region there is no direct evidence of salt (although it could be present at deep levels as no well has been drilled to sufficient depth to discount the presence of Cambrian strata). Reported hydrocarbon types indicate the presence of Silurian source rock and it is considered that this is the most likely horizon to contain the basal detachment – this is speculative. The style of the fold varies but in general they are characterized as assymmetric with a steep structurally thinned forelimb, an overthickened hinge and a relatively intact backlimb. The major fold often incorporates a pre-existing detachment in the Basal Fars succession that forms in evaporites and/or saliferous beds in the Basal Fars.

Slide 4: The core of the fold is structurally complex with a series of folds and small faults. The majority of these features formed as a result of volume constraints as a stronger, stiffer, and more competent unit is folded about an axis. In this case, this is a view of the Balambo Section within the core of the Asmer Anticline. The section has been folded and subsequently faulted as the degree of deformation continues.

Slide 5: Bedding (So) on the front limb of the fold is often rotated to near vertical. In this position the front limb is sheared with a series of faults that cut across the competent units and ride within the less competent units. The sense of shear is extensional relative to the bedding reference surface.

Slide 6: A schematic of the structural style. Bedding in the forelimb has rotated to near vertical and the bedding surface has rotaed from the zone of compression into the field of extension. Extension is accomplished through a series of bedding parallel shear surfaces that extend the beds vertically and thin the units horizontally. Although the structural style is contractional in nature it is common to see local extension on the front limb as a result of this rotation.

Slide 7: Review of the Structural Style

Slide 8: The fracture study was conducted on the Ajdagh Structure located to the southwest of the city of Sulaymaniyah in southern Kurdistan. The fold can be viewed on Google Earth and is a doubly plunging fold with a northern and southern plunge. From north to south the fold bifurcated into two separate folds. The study concentrates on the larger eastern fold. Immediately to the east of the Ajdagh Structure is another large anticline known as the Qara Dagh Structure (also referred to as the Segurma Structure). This fold is over 100 kilometers long and is a tight near isoclinal fold with vertical limbs and a structurally over-thickened hinge.

Slide 9: At its highest point, the Ajdagh Structure has the characteristic shape that was previously described. As the fold loses amplitude and displacement (?) to the south and the north the fold becomes more open and the forelimb is no longer rotated into the vertical field. Three transects were run across the structure as well as detail work along the Awa Spi (River) Gorge located in the backlimb of the southern portion of the fold.

Slide 10: A portion of an unpublished regional cross-section across the Agdagh and Qara Dagh Structures demonstrates the relationship between these two structurally positive features. In the Qara Dagh (Segurma) feature both fold limbs have rotated into the vertical position. Hinterland directed features are observed on the eastern limb of the fold that are interpreted to have formed as a result of volume constraint and are linked to the core of the structure. The Ajdagh Structure does not have the same degree of deformation in its shape. Based on seismic data and regional reconstructions it is interpreted that the Ajdagh structure is carried in the hanging wall of a foreland directed (to the southwest) minor thrust fault that plumbs to the basal detachment. The position of the basal detachment is speculative. To the north the basal detachment is know to lie within the Palaeozoic strata based on outcrop exposures. In this area the nature of the structural style within the Palaeozoic remains unknown. Basement is depicted to have been deformed as a series of re-activated down-to-the hinterland normal faults. Refraction seismic data indicates that the thickness of the crust is equal to estimates to the west within the Foreland Basin. This suggests that in this area, crystalline basement is not directly involved with the thrusting. To the north and east,

basement does become involved and many of the larger structures are cored with crystalline rock. On the seismic data an upward structural shift can be seen from the southwest (foreland) to the northeast (hinterland). This shift is interpreted to coincide with the reactivation of the deeper normal faults that cut through crystalline basement.

Slide 11: View of the Ajdagh Structure looking to the northeast. The front limb dips steeply to the west the hinge is shattered and the backlimb dips gently to the east

Slide 12: View to the southeast looking along the hinge and the front limb of the Ajdagh Anticline. The basal Fars detachment is folded over the structure. A series of minor detachment folds developed lie above the Lower Fars Detachment that are not related to the larger underlying Ajdagh Structure.

Slide 13: The Awa Spi Gorge (*Spi is kurdish for River*). Three traverses were laid out along the gorge to measure fracture orientation and intensity.

Slide 14: Measuring the fractures was accomplished by placing a spotter on one side of the gorge and the measuring team on the other side of the gorge. It is difficult to see the extent of the fracture when standing directly upon it so the spotter could provide perspective and keep the measuring team moving efficiently. Attempts were made to climb up and down the gorge but this proved to be impractical.

Slide 15: Two dominant fracture orientations were observed. Poles to fractures show two clusters of near vertical fractures. A dominant set is developed that trends perpendicular to the fold axis at approximately 260 – 080. This set would be equivalent to the Type I set put forward by Sterns. A second orientation was observed that trends at approximately 315 – 135 and does not fit any of the standard models used to describe fractures associated with folds. The 315 – 135 set is subordinate to the dominant set.

Slide 16: The relationship of the two fracture sets is well exposed in the outcrop. The large throughgoing fractures are the dominant set and appears to truncate the subordinate set. It is tempting to assume that the dominant fracture set is younger as it appeares to cut the subordinate set but upon closer inspection it can be seen that the subordinate set id defined by the dominant set and that the subordinate set intensity appears to be controlled by the dominant set. Likely the relationship is that the two sets formed at the smae time and is possibly related to the transpressional motion of the system.

Slide 17: The description of fractures can be problematic. Typically geoscientist are able to describe fracture intensity qualitatively but it is difficult to quantitatively describe fractures and attempts to do so are fraught with uncertainty and concerns of sampling bias. One way of describing the fractures is born out by recognising that fracture distribution is a spatial series. Most types of fracture measurements can be reduced to describing the number of fractures per unit distance. A series has certain properties within it that can give a more accurate description of the distribution other than the simple number of occurrences per unit distance. In this case

the length of each fracture is plotted along the length of the transect. The data was collected and measured to the nearest decimetre in this example.

Slide 18: Once the series is established a series of summing operators can be run along the series to try to establish the shape of a waveform in the series. In this case a summing window was run along the series and the sum of the lengths of all the fractures within the window were summed and plotted at the centre point of the window. The window is then shifted forward one increment (or sample interval) and the summing operation is repeated. The length of the window can be adjusted.

Slide 19: This is the same series after a 1.0 metre window was run along the series. The amplitude of the series has increased and the series of spikes that were observed on the previous slide has now some bandwidth as a result of the summing window

Slide 20: In this case the summing window is 10.0 metres wide and a waveform in the resulting function can be observed. The waveform lends itself to ready analysis by using a Fourier Transform.

Slide 21: A Fourier Transform of Traverse #1 after the 10.0 metre smoothing reveals a dominant spatial frequency to the distribution of fractures along the traverse. The horizontal axis is in units of cycle/metre. The inverse of this number will be the dominant period of the fracture distribution. Using this tool it is possible to make predictions on the distribution of the fractures by establishing the amplitude of the dominant period against the background amplitude. In this case there is a spike at 0.005/metre, which equates to a period of 200 metres. Although the approach can predict these longer wavelengths it should be noted that the length of the traverse is less than the predicted length of the dominant period so that it should be viewed that the sample length of the traverse under-represents the dominant period and there is greater uncertainty in the final results. Given that there is useful information in the approach. The analysis would indicated that every 200 metres (1/0.005 cycles/m) it would be expected that there would be a significant fracture swarm. This number is useful in the design of an operation that is intended to intersect fracture systems, for example a horizontal well The area under the curve represents the total energy or in this case the total fracture intensity in the system. In effect it is a means of directly comparing one area to another in terms of fracture intensity. However it should be remembered that the total fracture intensity is also a function of the length of the traverse. The area under the graph divided by the length of the traverse gives the fracture intensity per unit distance and describes the fractures in units that are familiar, which can be compared to other areas, layers, etc.

Slide 22: Analysing fracture patterns from outcrop is reliable but is manpower intensive and is inherently dependent on the outcrop pattern and ease of access. Satellite imagery is a useful tool to quickly extend the scope of a fracture study. In this case QuickBird $_{TM}$ data images the fracture system. The satellite data is limited in part as it is only able to track the trend of the fractures, the dip of the fractures remains unknown. Ground truth along the Awa Spi Gorge has confirmed that the fractures are predominantly vertical. The satellite data allows for the length

measurement of the fractures over a greater area than could be efficiently recorded directly on the ground. A transect line was drawn on the image and each fracture was projected into the scan line.

Slide 23: The summing curves described previously were calculated for the scan line across the satellite image. In this case all summing curves are displayed on the same graph to compare the effect of the different summing window lengths. The two large spikes on the left end of the curve (580 m and 730 m) are minor vertical faults that cut across the scan line

Slide 24: The Fourier Transform of the 10 metre summing window indicates the same peak at 0.005 cyles/metre. In this case the length of the scan line is significantly longer than the dominant period of the fracture intensity suggesting greater confidence in the dominant fracture swarm occurrence. Although the data set that derived this fracture distribution is different from the outcrop study it is interesting to note that the standardized fracture intensity per unit length is similar and the dominat period is similar as well. The conclusion is that the QuickBird data is accurate in its ability to image the fracture pattern in the Ajdagh Anticline. Other peaks are also identified.

Slide 25: The front limb of the structure is difficult to do a surface study due to its steeply dipping surface. The same satellite data is helpful in analysing the fracture distribution. Some graphic manipulation is required to account for the steep dip of the bedding. Having accomplished this the front limb may be analysed.

Slide 26: A close-up of the front limb. The fracture distribution is clearly imaged by the satellite data.

Slide 27: Summing curves from a scan line along the front limb taken from the satellite data.

Slide 28: Fourier Transform of the 10 metre summing curve. The period of the dominant fracture system is 0.034 cycle/m (33 metre period), which differs from the data collected at the Awa Spi Gorge. The fracture intensity per unit length is greater indicating that the amount of strain represented by fracture development is greater on the forelimb as compared to the backlimb.

Slide 29: Distribution of the calculated fracture intensity shows that there is greater fracture intensity on the front limb as compared to the back limb.

Slide 30: Fourier Analysis of fracture systems is a relatively easy process that can be done with a spreadsheet and simple programs that can be downloaded inexpensively from the internet. The uses and applications of Fourier Analysis in defining and quantitatively analysisng fracture sytems is very promising. Results from these types of analysis can be placed directly into reservoir simulation modelling packages to give an accurate portrayal of the fracture

system within the reservoir and hopefully give greater confidence in estimating permeability within the reservoir.

Slide 31: This work is the product of extensive discussions the authors had with the staff of WesternZagros Resources. The work was greatly improved with the comments made by the technical staff at WesternZagros

Slide 32: Invaluable help was provided in the field by Dr. Fahdil Lawa and Dr. Dler Baban. Their intimate knowledge of the stratigraphy of southern Kurdistan, their enthusiastic willingness to help in the field, and their kind and pleasant disposition made the work possible. The additional help by the mine safety crew (represented by Mr. Jeba) and in-country safety experts were unfortunately necessary and greatly appreciated.