FAULT GEOMETRY AND DEPTH OF DETACHMENT IN ANAH GRABEN – WEST IRAQ

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ABSTRACT

Fault shape at depth and the depth to the corresponding detachment were estimated from calculating bed length and excess area balance in cross–section and graphically from associated hangingwall roll–over fold profile.

Six different construction techniques were used on the same initial cross–section which is derived from converting a chosen seismic profile to a true depth section with equal vertical and horizontal scales. The graphical construction techniques include Chevron, modified Chevron, inclined shear, constant – slip, and flexural – slip models. Because these construction models vary considerably, since they assume different mechanisms by which the hangingwall deforms, the resultant fault shapes and their corresponding detachment depth differ according to the construction technique used. Therefore, the geometric construction models cannot provide a unique answer about the geometry of a listric normal fault at depth and the depth at which it flattens, particularly in areas of limited seismic and well data. They may define a range of possible solutions. However, the constructions show that the fault soles at deep level irrespective of the technique used. The results show good agreement with the available geophysical and geological information.

الشكل الهندسي للصدع وعمق سطح الانفصال في منخسف عنه – غرب العراق

صفاء الدين فخري فؤاد

المستخلص

تم تحديد شكل الصدع مع العمق إضافة الى تقدير عمق سطح انفصاله عن طريق حساب أطوال الطبقات وموازنة المساحة في المقطع وكذلك بطرق بنائية بيانية مشتقة من شكل مقطع الطية المرافقة للجانب المتكئ من الصدع . تم تحويل مقطع زلزالي زمني مختار الى مقطع عمقي حقيقي بمقياس أفقي وعمودي متساوي ثم طبقت ستة طرق بنائية مختلفة على هذا المقطع . ولما كانت طرق البناء تختلف لكونها تفترض ميكانيكيات تشويه مختلفة للجزء المتكئ من الصدع، كانت نتائج تقديرات شكل الصدع وعمق سطح الانفصال مختلفة باختلاف طرق البناء المستخدمة.

وعليه فأن طرق البناء لا تعطي تقدير موحد عن شكل الصدع مع العمق و عمق سطح انفصاله وبالأخص في المناطق ذات المعلومات الزلزالية و الجيولوجية المحدودة إلا أنها تعطي مدى من التقديرات المحتملة. وعلى أي حال فأن عمق سطح الانفصال في المنطقة المدروسة كان عميقا بغض النظر عن طريقة البناء المستخدمة.

ان النتائج المستحصلة قد جاءت منسجمة مع المعلومات الجيوفيزيائية والجيولوجية المتوفرة عن المنطقة .

INTRODUCTION

Anah Graben is an ENE trending, 250 Km long and 7–20 km wide subsurface graben extending from Al-Qaim town near the Iraqi–Syrian borders eastwards to the vicinity of the Tharthar valley (Fig.1). It is an intercontinental rift basin formed during the Campanian–Ma'astrichtian and was subsequently filled by Upper Cretaceous syn–rift sediments that display a dramatic thickness increase within the fault bounded basin. The active basin subsidence was terminated by the

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end of the Ma'astrichtian, and then followed by deposition of relatively thin Tertiary post–rift sediments. The tectonic and the structural evolution of Anah Graben have been discussed in details by Fouad (1997).

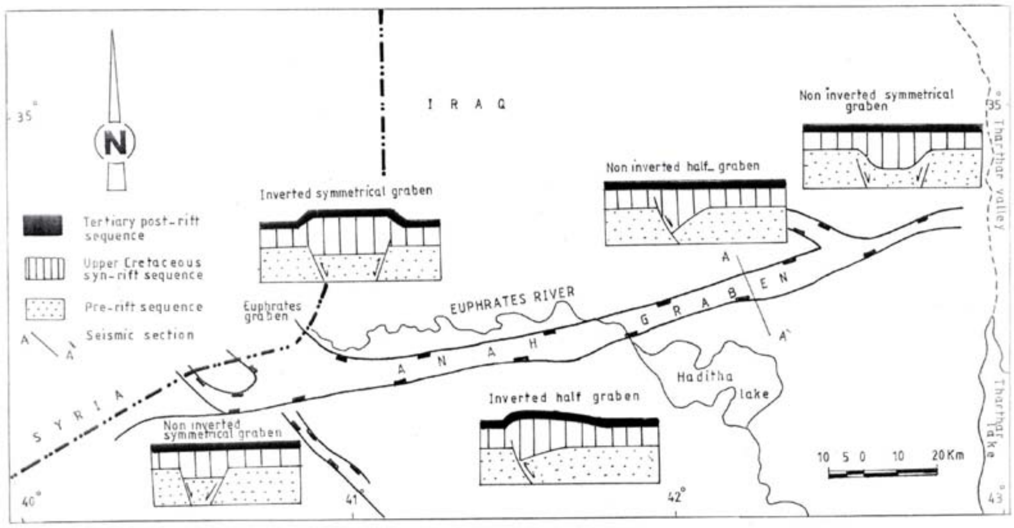

Fig. (1): Structural outline map of Anah Graben showing the variation in the structural styles (Segments) along its strike (after Fouad, 1997)

Anah Graben actually consists of a number of segments with different structural styles. According to Fouad (1997), the graben is subdivided into five main segments. They are, from east to west, non inverted symmetrical graben, non inverted half – graben, inverted half – graben, inverted symmetrical graben, and non inverted symmetrical graben (Fig.1).

The available reflection seismic data of the study region are of poor quality, particularly of the second segment (the non inverted half–graben style). The aim of the presents study is to predict the geometry of the basin bounding fault at depth and to estimate the depth of the detachment in this particular segment, using simple area balance technique aided by several graphical construction methods.

IDENTIFICATION OF THE SEISMIC REFLECTORS

The seismic data of the region is of poor quality in general. Nevertheless, in the seismic section (A–A\) which passes across the graben, two seismic marker reflectors were identified (Figs. 2 and 3). Based on OEC (1980), Fyodorov (1981and 1982) and Fouad (1997) the upper seismic reflector (the H2 marker) represents the Upper Cretaceous erosional surface and accordingly represents the top of the syn–rift sequence. On the other hand, the lower seismic reflector (the H3 marker), which is erosional surface between the Upper Cretaceous units and the underling (older) sediments, represents a seismic marker denoting the top of the pre– rift sequence.

STRUCTURAL INTERPRETATION OF THE SEISMIC SECTION

In the seismic section (A–A\) the rift basin appears as a half–graben bounded by one master normal fault with maximum vertical throw of about (0.5) sec. The fault plane is poorly detected. However, the pre–rift sequence appears forming a broad and gentle hangingwall roll–over fold (Fig.2). The roll–over fold is a good indicator that the associated fault is listric, because extensional movement on listric (i.e. concave upward) faults only can generate roll–over folds (Gibbs, 1983, 1984; Xiao and Suppe, 1992; Mitra, 1993; Schlische, 1995). Therefore, it is suggested that the master basin boundary fault, in this section is a south–dipping listric normal fault. The fault appears to displace the entire pre–rift sequence. The syn–rift sequence appears to be displaced too, except its uppermost part. The syn–rift sequence displays an abrupt thickness increase in passing from footwall to hangingwall (Fig. 2 and 3). Furthermore, the syn–rift units, which show onlap stratal pattern onto the basin boundary, progressively thins southwards away from the boundary fault. They regain their regional level and original thickness when the boundary listric fault flattens to a regional detachment (point R in Fig.3). On the other hand, the Tertiary sequence which represents the post–rift sequence appears horizontal with parallel reflection signature and uniform thickness in passing across the graben indicating a period of uniform deposition across the entire region at the time of their deposition.

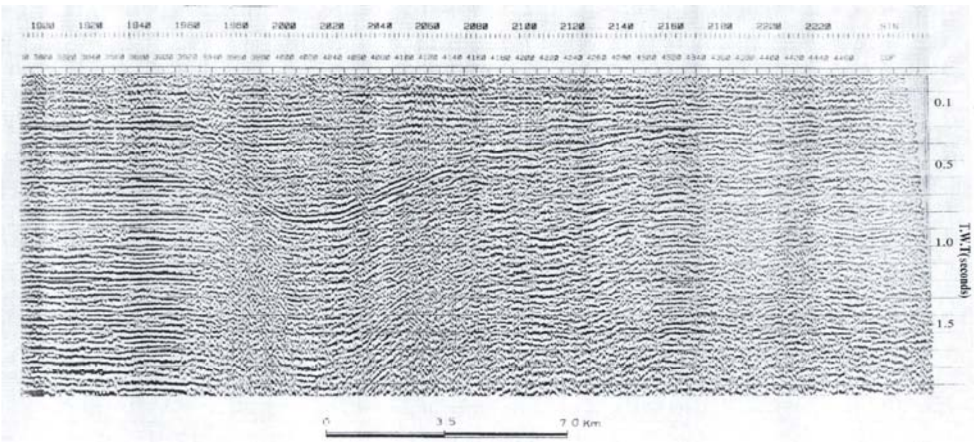

Fig. (2): Seismic section A–A\ showing the half graben geometry of Anah rift basin

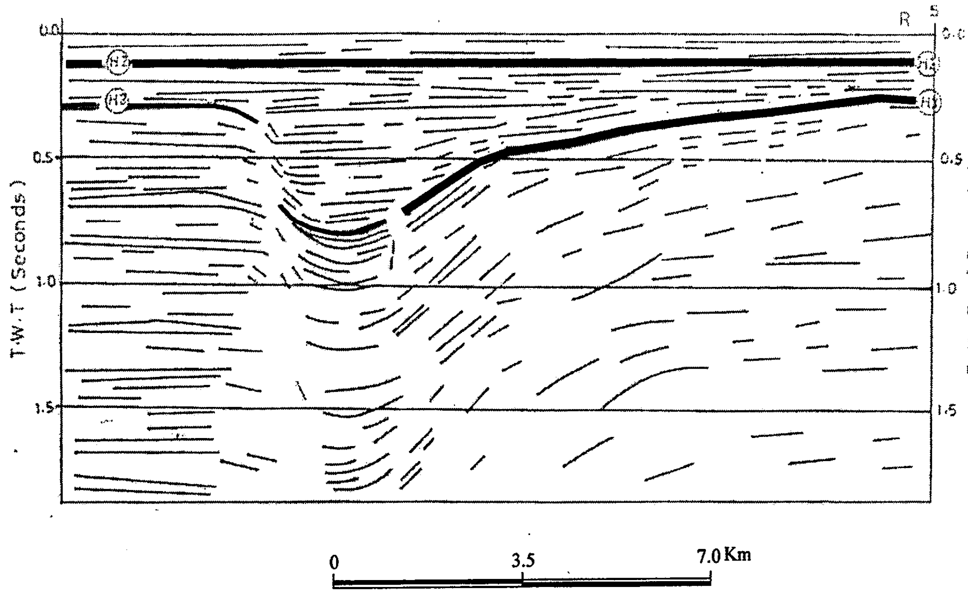

Fig. (3): Line drawing and interpretation of seismic section A–A\

DEPTH TO DETACHMENT AND FAULT GEOMETRY AT DEPTH

Estimation of detachment depth by using simple area balance techniques was first applied to contractional terrains (Dahlstrom, 1969;and Hossack, 1979). Gibbs (1983) showed that the same principle can be applied to regions of extensional tectonics. If well and seismic data in a specific region are of poor quality (such as in Anah region), it is possible to calculate depth to detachment and to predict listric fault geometry at depth by using geometrical section balancing techniques (Gibbs, 1983 and 1984). They can be derived from calculating bed length and excess area balance in cross–section as well as graphically from the associated hangingwall roll–over fold profile. These techniques rely on the following fundamental assumptions (White et al., 1986; Withjack and Peterson, 1993):

1. The section must be oriented along the direction of tectonic transport and perpendicular to the axis of the rift.
2. All deformations occur within the plane of the section and there is no movement out of the plane of section; plane condition, or conservation of cross–sectional area.
3. The footwall remains undeformed throughout.

Consequently, these geometrical techniques are not applicable in areas of active salt or shale diapirism, or for normal faults with considerable strike–slip displacement, because rock material can be moved in or out of the plane of section, therefore breaking the plane strain rule (Withjack and Peterson, 1993; Coward; 1996; Hauge and Gray, 1996).

For the purpose of the present study, seismic section (A–A\), (Figs.1 and 2) is chosen to section balancing for the following reasons:

1. The section is perpendicular to the graben axis (Fig.1) and paralleled to the tectonic transport direction.
2. The section shows a prominent hangingwall roll–over fold that can be used in the graphical construction of the fault geometry at depth.
3. Bed length and fault displacement are clear and measurable.

The chosen seismic section was converted to a true depth section with equal vertical and horizontal scales. This is because angles, line lengths and areas are not preserved in time domain (Gibbs, 1983; Rowan and Kligfield, 1989and Buchanan, 1996). The top of the pre–rift units in the resultant cross–section was then used as a marker horizon for construction, because it is clear and traceable throughout the section (Fig.3), and because pre–rift units record the total amount of normal displacement, whereas syn–rift units may record only a portion of the normal displacement (Mitra,1993).The regional level of this marker horizon (i.e R point, pin position) is located through removal of the effects of faulting and folding (Cooper et al.,1989). This level is projected from footwall to hangingwall (Fig.3). After that, the area and bed length can be measured directly.

DEPTH TO DETACHMENT CALCULATION USING AREA AND BED LENGTH BALANCE TECHNIQUE

Listric normal faults tend to flatten downwards. They may become horizontal at depth. This geometry results in a dominantly horizontal movement above detachment (White et al., 1986; Mitra, 1993). Fig. (4) shows a listric normal fault that becomes horizontal at depth. The geometry before movement is shown in Fig. (4a). If movement occurs and the section is extended by (e), the geometry would look like Fig. (4b). If there is no movement out of the plane of section, area (A) is equal to area (B). Consequently, the hangingwall deforms, filling the gap beneath it. This leaves a space (area C) above (White et al., 1986 and Schlische, 1995), such that:

area A = area B = area C (Fig.4c)

In other words, the area removed from the cross–section (area C) is the same as the area (area A) added to the cross-section (Gibbs, 1983 and 1984;White et al., 1986 and Williams and Vann , 1987). Area (A) is the product of the extension (e) and detachment depth (D), so

area C = area A = eD ……….(1)

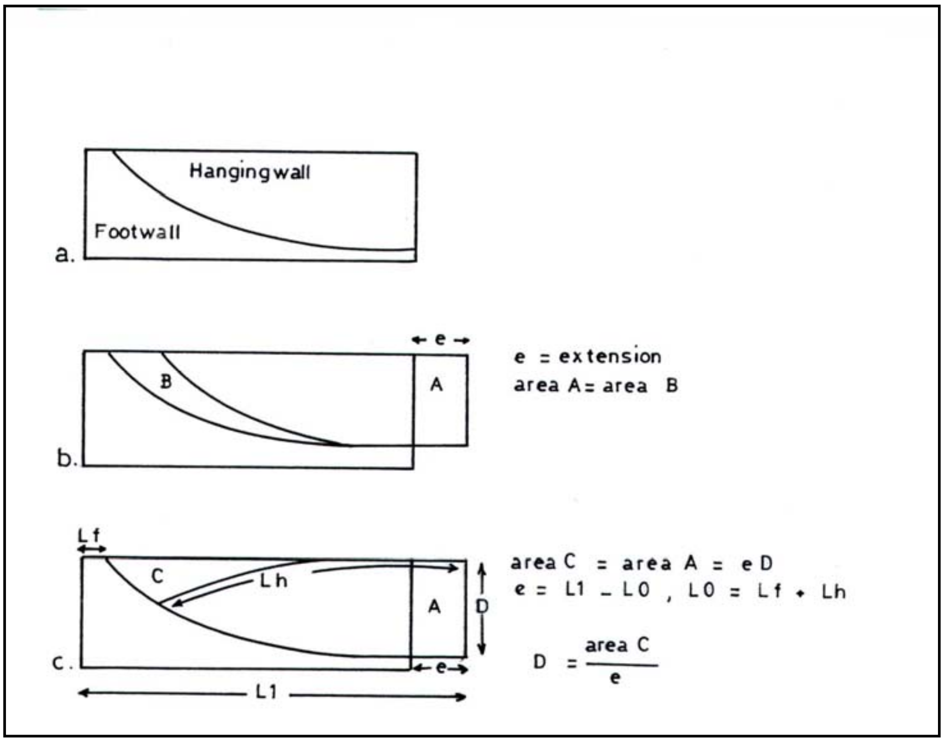

Fig. (4): Diagram to illustrate the deformation of the hangingwall to fill the potential void beneath it. (a) initial stage (b) after extension (e) (c) hangingwall deformed by roll-over folding. Parameters used in area balance calculation are also shown in (c).
Area (A) = area (B) = area (C)

Area (C) can be calculated directly from the cross–section. Total extension (e) may be calculated using bed length techniques (Hossack, 1979 and Gibbs, 1983) so

$$e = L_1 - L_0 \;\ldots\ldots\ldots\ldots\ldots\ldots.. (2)$$

Where (L_1) is the measured deformed section length, and (L_0) is the original bed length which can be calculated by summing the footwall (L_1) and hangingwall (L_h) bed lengths (Fig. 4c).

Accordingly, the depth to detachment (D) can be calculated by the equation

$$D = \frac{\text{area (C)}}{e} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Applying equation (3) to the depth converted seismic section A–A\ (see Fig.11) the depth to detachment is calculated to be 9.375 Km.

CALCULATION OF DETACHMENT DEPTH AND SHAPE OF LISTRIC NORMAL FAULT AT DEPTH USING ROLL–OVER FOLD GEOMETRY

As mentioned earlier, displacement on listric normal fault generates a hangingwall roll–over fold by a mechanism known as fault – bend folding (Suppe, 1983 and 1985; Mitra, 1993 and Schilsche, 1995). Verral (1981) was the first to note that the shape of the hangingwall roll–over is in some way related to the underlying fault geometry. He made the first important contribution to the calculation of listric normal fault profile and depth to the corresponding detachment by using the hangingwall roll–over shape. His graphical method is known as "The Chevron Construction".

Since then, several graphical techniques and physical models relating listric normal faults to their hangingwall deformation have been introduced (e.g. Gibbs, 1983 and 1984; Davision, 1986, White et al., 1986; Williams and Vann, 1987; Wheeler, 1987; Groshong, 1989; Rowan and Kligfield, 1989; White and Yielding, 1991; Xiao and Suppe, 1992; Matos, 1993; Whithjack and Peterson, 1993; Withjack et al., 1995 and Hauge and Gray, 1996).

According to Rowan and Kligfield (1989), the formation of hangingwall roll–over can be expressed as two–stage process (Fig.5): In the **first stage**, during an increment of tectonic extension, points within the hangingwall (e.g. point A in Fig. 5b) are displaced sideways to new positions above the listric fault (e.g point A'), creating avoid between the hangingwall and the footwall. In the **second stage**, the roll–over anticline is created as points within the displaced hangingwall drop down under the effects of gravity to rest upon the undeformed footwall. The possible net displacement vectors of the second stage (the arrows in Fig. 5c), may be vertical (A' to A''), oblique antithetic (A' to A'''), oblique synthetic (A' to A''''), or variable (not shown), resulting in different roll–over geometries (Fig.5d). Depending on the way by which the hangingwall deforms, the construction techniques are broadly classified into three categories: **Shear, Flexural-slip** and **Constant-slip models**. In the present study different construction techniques will be used. The results will be then compared and discussed in order to infer the best fitting models.

1- Shear models

These models assume that hangingwall deform by bulk simple shear on closely spaced planes, which can be either vertical (Verrall, 1981; Gibbs. 1983 and 1984; Williams and Vann, 1987) or inclined (White et al., 1986; White and Yielding,

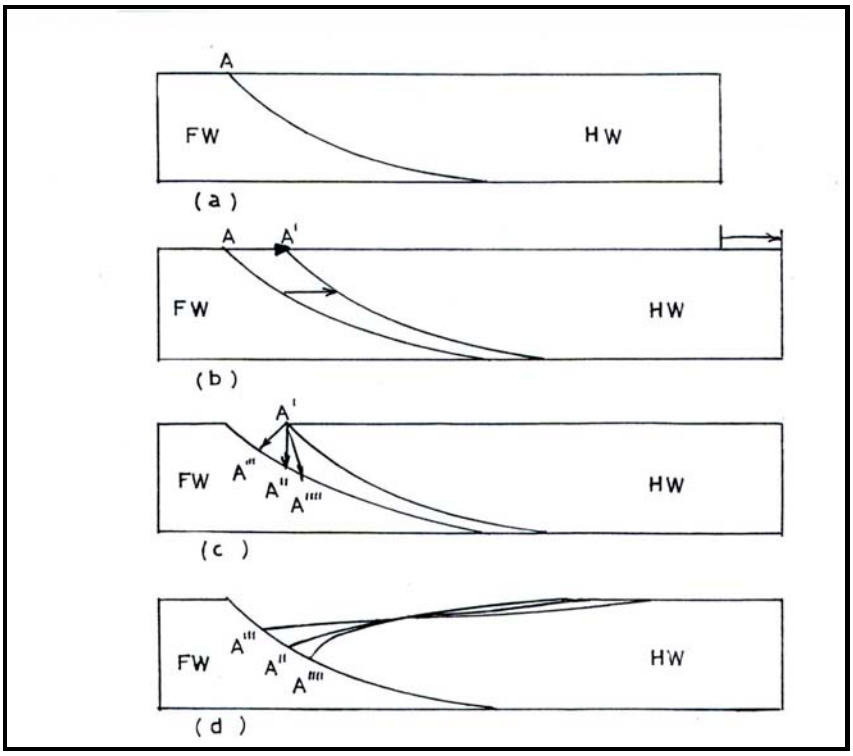

Fig. (5): Hangingwall roll-over development above listric normal fault. (a) initial stage. (b) horizontal displacement during increment of tectonic extension shown by arrows. (c) possible displacement vectors of hangingwall material as it deforms to fill void. (d) resultant roll-over shapes (after Rowan and Kligfield, 1989).

1991; Withjack and Peterson 1993 and Hauge and Gray, 1996). Three models are discussed:

- **The "Chevron Construction"**

The "Chevron Construction" (Verrall, 1981) is the first construction technique used to construct listric fault shape from a roll–over profile. It is also referred to as the vertical shear construction. Displacement (d) on normal fault (Fig.6) may be resolved into a horizontal component of heave (h) and a vertical component of throw (t). In this technique the hangingwall material is assumed to have moved laterally a constant amount (the heave h) and to have slide vertically under the effect of gravity to stay in contact with the fault surface (path A to A' to A " in Fig.5). Accordingly, the heave (h), which is the primary consideration in this construction, is assumed to be conserved, whilest both displacement (d) and throw (t) vary with the fault dip angle. The theoretical aspect behind this construction is discussed in detail by Verrall (1981) and Gibbs (1983), and is presented here in a graphical form. In (Fig.6), the regional level is first projected from footwall to hangingwall, then subdivided into equal spaced intervals of one heave unit (h), (AB, BC, CD…etc). A vertical grid is then projected through the points (B, C, D….etc.) to define points (A', B', C'…etc.) on the roll–over. The diagonal (BB') represents the resultant vector of heave and throw in this segment, and it is parallel to the displacement direction along the fault. Therefore, (BB') is parallel to the fault profile in this segment which may be constructed by drawing a line through (A') parallel to (BB'). This procedure may be continued for all the other heave segment of the roll–over profile and the fault geometry is completed (Fig.6). By applying this construction technique on the depth–converted seismic section (A–A'), the fault shape is constructed (Fig.11 profile 4) and the depth to detachment is estimated to be (8.75) Km.

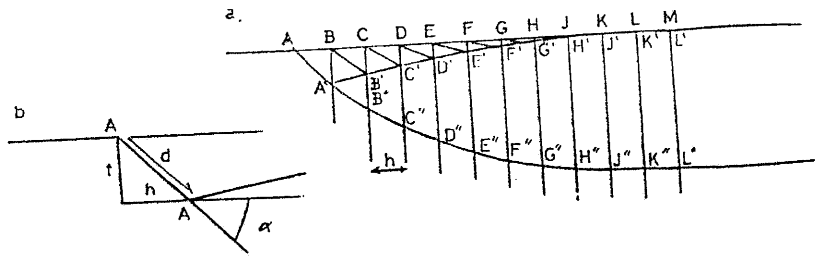

Fig. (6): (a) The Chevron construction for fault profile using hangingwall roll-over geometry. The vertical grid had a horizontal spacing of 1 heave unit. Diagonals draw from regional to roll-over (e.g. B B') parallel to the fault in that heave segment. (b) Detail of fault to show displacement resolved into vertical throw and horizontal heave components ∝ is the dip of the fault (after Verrel, 1981 and Gibbs, 1983).

Modified Chevron Construction

This construction technique, assumes conservation of fault displacement (d) and both heave and throw vary with the fault dip angle (Fig.7). The construction procedure, which is introduced by Williams and Vann (1987), is similar to the vertical shear construction, except that the fault displacement is the primary consideration instead of the heave. The construction procedure involves measuring of the displacement (d), which is the primary measure, between the displaced parts of the reference bed (AA' in Fig.7). A vertical line through (A') is constructed to meet the regional level at (B).

A line of one displacement unit (d) is drawn from point (B) to touch the roll-over defining point (B"), This is obtained by construction an arc of radius (d), centered at (B), which intersects the roll–over profile at (B"). The line (BB") is parallel to the displacement vector for this segment is drawn through A" and parallel to (BB"). A vertical line is drawn through (B") to define (C) on the regional level and the entire fault geometry can be constructed by repeating the procedure on the roll–over profile (Fig.7). Using the Modified Chevron Construction Technique on the seismic section (A–A"), the fault geometry is constructed (Fig.11, profile 3) and the depth of its corresponding detachment is calculated to be (8.5) Km.

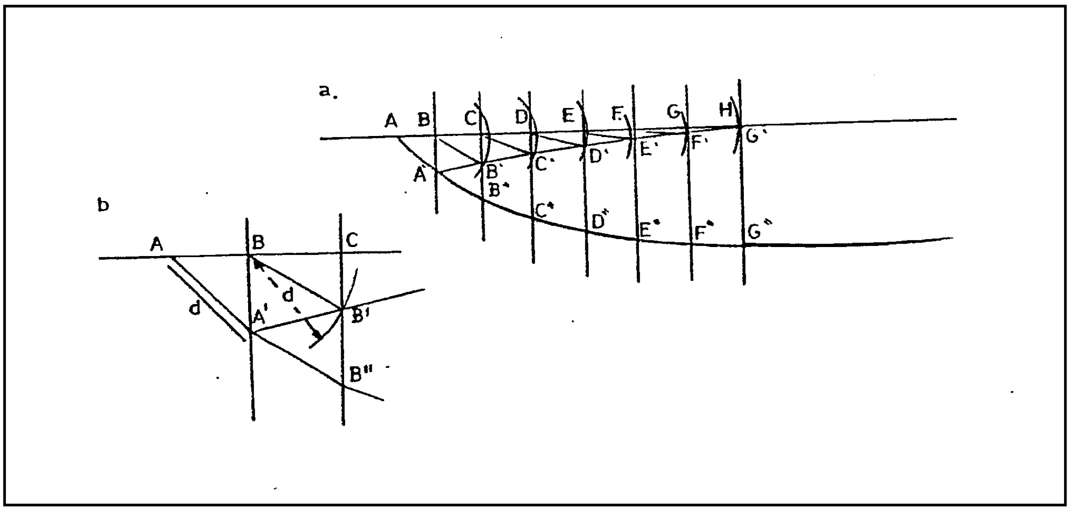

Fig. (7): (a) Modified Chevron construction for fault profile using hangingwall roll-over geometry. (b) Detail of construction technique. Vertical line through A' defines B at regional intersection. Arc of radius d intersects. roll–over at B'. Fault drawn parallel to B B' through A' (after Williams and Vann, 1987).

- **Inclined shear construction**

In contrast to the vertical shear models, it is also possible that most of the hangingwall deformation may be represented by inclined planes (non–vertical simple shear) as discussed by White et al., (1986), Rowan and Kligfield (1989), White and Yielding (1991), Withjack and Peterson (1993); Matos (1993). Withjack et al., (1995) and Hauge and Gray (1996). This model was first developed by White et al., (1986) to relate the hangingwall roll–over geometry to the fault geometry. The method follows the same procedure as the vertical shear method, except that the deformation of the hangingwall occurs in inclined planes (path A" to A"', in Fig.5).

In inclined shear angle (α) is the acute angle between the vertical and the inclined shear directions towards the listric fault (Fig. 8). This angle is unlikely to be greater than (60^o) (White and Yielding, 1991). In general, there is no agreement on the value of this angle, and different values were proposed by different authors e.g. White et al., 1986; White and Yielding, 1991; Withjack and Peterson, 1993 and Huage and Gray, 1996. Usually, this angle is specified by the user, but it could be estimated more accurately from the dip angle of the associated minor antithetic faults, if present.

It is not worthy to mention that the inclined shear model requires true extension amount greater than measured heave (White et al., 1986 and Rowan and Kligfield, 1989). This "modified" heave can be calculated by using simple equation that depends on the value of the inclined shear angle (Fig.8). The construction similar to the vertical shear, except that the regional level is subdivided into equal spaced intervals of unit length (h) $(1 + \tan \Theta \tan \alpha)$, where (h) is the heave, (Θ) is the dip of the fault, and (α) is the specified inclined shear angle (Fig.8). An inclined grid is constructed through (B, C, D…etc.) to define (A', B', C'….etc.) on the roll–over. The inclination of the grid is equal to the value of the inclined shear angle (α). The diagonal (BB') is drawn, which is parallel to the fault surface at that segment. The fault is drawn then through (A") and parallel to (BB'). The procedure may be continued until the fault geometry is completed (Fig.8).

Applying the inclined shear method to the seismic section (A–A') by using inclined shear angle of (10) degrees (as inferred from the dip angle of the associated antithetic faults), the geometry of the fault is constructed at depth and depth to line corresponding detachment is estimated to be (7.3) Km (Fig. 11, profile 2).

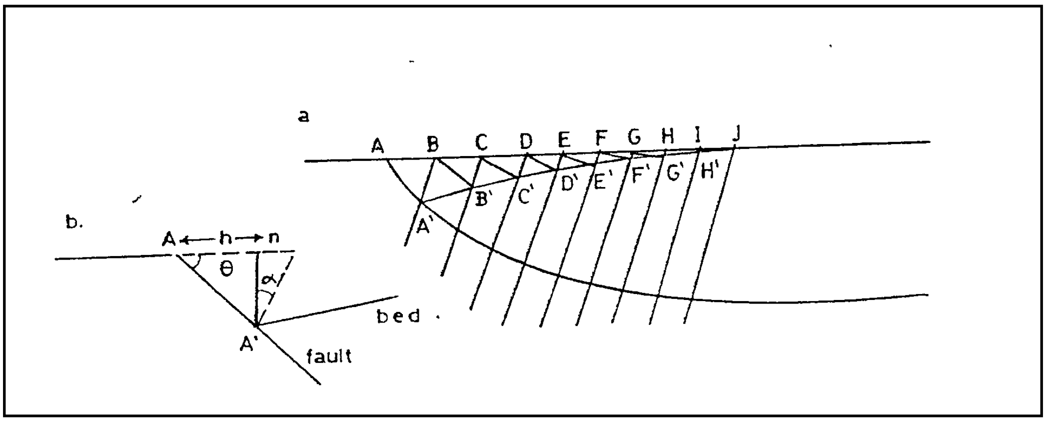

Fig. (8): (a) The inclined shear construction for fault profile using hangingwall roll-over geometry. The inclined grid has horizontal spacing of h $(1 + \tan \theta \tan \propto)$. (b) Detail of fault to show the horizontal extension (hn) where (h) is the heave, θ is the dip of the fault and $\propto$ is the inclined shear angle (after White et al., 1986).

2- Constant – slip model

In this model, which also referred as slip–line construction, it is assumed that the amount of slip at any point along the fault plane during extension is conserved along slip–lines which are curved trajectories parallel to the listric shape of the fault (Williams and Vann, 1987; White and Yielding, 1991 and Matos, 1993). According to Williams and Vann (1987), the slip–line construction uses displacement (d) as the primary measure and the hangingwall deformation is considered in terms of fault perpendicular displacement segments rather than vertical heave segments. This is represented in a graphical form in Fig. (9). The construction technique is facilitated by the use of paper or card template cut to the size of the displacement (d) segment. There is a unique position where the rectangular displacement segment of length (d) touches both the projected regional level and roll–over profile. The two points where length (d) touches regional and roll–over profile are labeled (B) and (B') and this line represents a slip–line parallel to displacement vector for the second displacement segment (Fig. 9). The fault segment is constructed from point (A') parallel to (BB') defining point (B"). Repeating the procedure through (B"), the rectangular displacement segment defines points (C, C' and C") on the regional level, roll–over profile and fault surface respectively. By repeating the procedure the fault geometry can be constructed (Fig. 9).

Using this technique on seismic section (A–A"), the fault geometry is constructed and shown in Fig. (11, profile1). The depth to the detachment is estimated to be (6.6) Km.

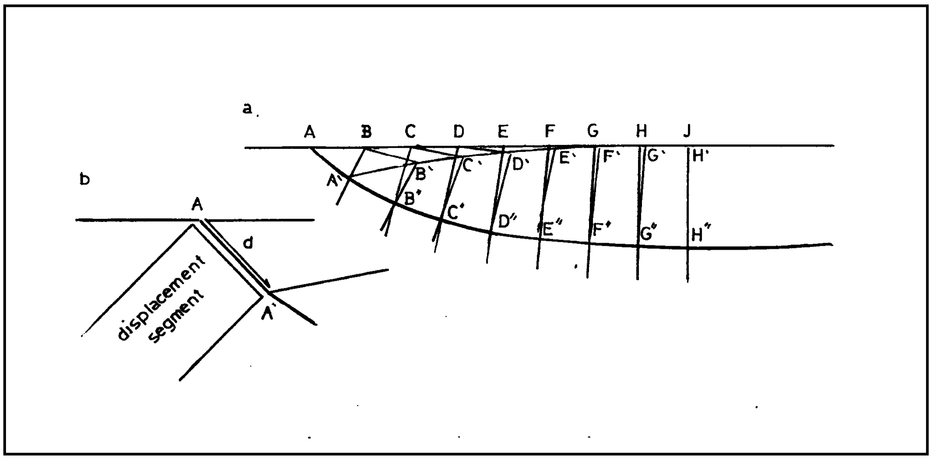

Fig. (9): (a) Slip–line construction for fault profile using hangingwall roll–over geometry. Displacement segment dimensions are conserved (e.g. B B' = C C' = d). (b) Detail of rectangular displacement (A A' = d) (after Williams and Vann, 1987)

3- Flexural – slip model

The model assumes that well developed plane–parallel stratification within the hangingwall allows deformation to occur by flexural–slip mechanism. The prime consideration in this method is the conservation of bed–length and orthogonal thickness. This implies that displacement occurs in vertical heave segments of variable width. The theoretical consideration behind this construction is discussed by Davison (1986), and represented in graphical form in Fig. (10). A vertical lines is drawn from (A) to meet the regional level at (B). Arc length (La), which is the heave, is laid out along the down faulted bed from (A) to define (C). A vertical line is then drawn from (C) to meet the regional level at (D), which intern defines a horizontal distance (BC), which is equal to (lb). Arc length (lb) is laid out from (C) to define, (E) and so on, until the last Arc length laid out lies parallel to the regional level.

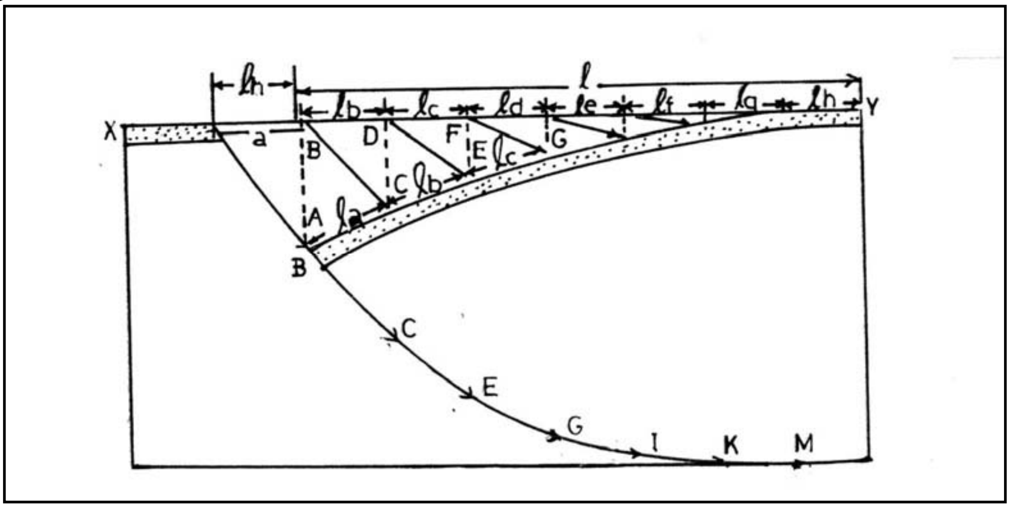

Fig. (10): Flexural – slip and bed – length balance technique. See text for explanation (after Davison, 1986)

Diagonals (BC, DE, FG, etc.) are parallel to the fault surface. The fault may then be constructed from (A) to (C), (C) to (E), (E) to (G) etc. until the fault construction is completed. Using flexural-slip and bed length balance method on the seismic section (A–A'), the fault geometry is constructed as shown in Fig. (11, profile 5) and the depth to the corresponding detachment is estimated to be (9.0) Km.

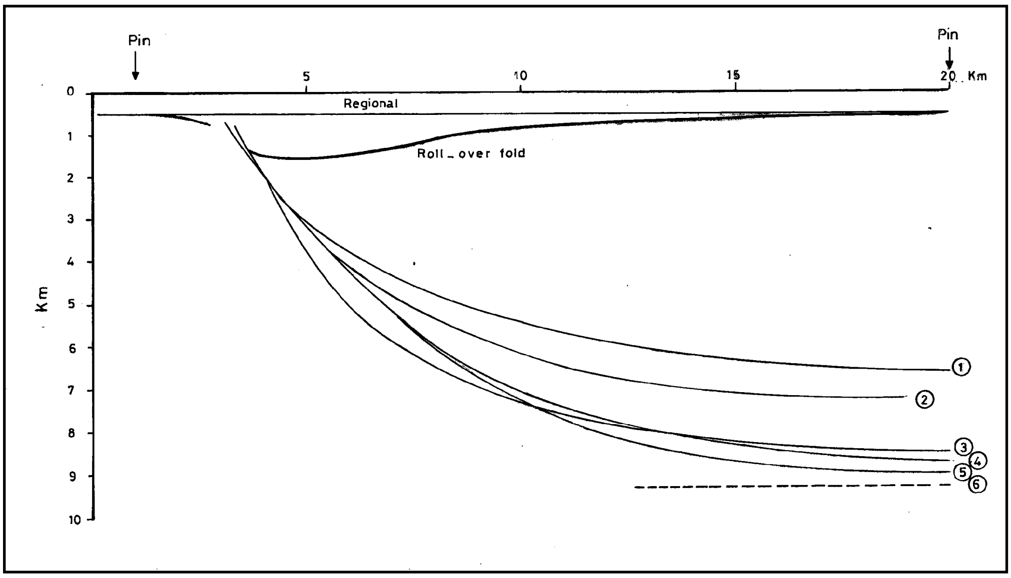

Fig. (11): Fault profiles and depth to detachment using six different techniques on the same roll–over geometry. 1. Slip–line construction, 2. Inclined shear construction. 3. Modified Chevron construction, 4. Chevron construction, 5. Flexural–slip and bed length balance construction and 6. Area balance with bed length conservation technique. Depth converted seismic line (A – A') with equal horizontal and vertical scale.

DISCUSSION AND CONCLUSIONS

Numerous balancing models have been proposed in the literature to construct fault geometry at depth and the corresponding detachment depth based on geometrical balance and roll–over profile. The geometry of a roll–over fold is controlled by the shape of the fault surface and the mechanism by which the hangingwall deforms to fill the potential void beneath it (Rowan and Kligfield, 1989 and Schlische, 1995). Therefore, construction models vary considerably because they assume different hangingwall deformation mechanism (e.g. vertical shear, flexural–slip….etc). Each model has its advantages and limitations. Shear models in general, conserve cross–sectional area but do not conserve bed length and orthogonal thickness because they assume that the formation of the hangingwall roll–over is achieved by shear (similar) folding (Gibbs, 1984 and Matos, 1993). On the other hand, in the flexural–slip model, bed length and orthogonal thickness of the layers remain constant, but the displacement along the fault is not preserved (Davison, 1986). Objections to this model include the fact that antithetic and synthetic faults are often observed within the hangingwall block disrupting the layering and thus will inhibit inter–bed slip. Also thickness variations such as those associated with growth faults may cause problems since plane–parallel stratification is required for inter–bed slip (White and Yielding, 1991). Constant–slip model fails to conserve the mass (Wheeler, 1987and White and Yielding, 1991). Therefore, using the same initial hangingwall data, fault shapes and detachment depths differ according to the construction method used. This is shown in Fig. (11), where different construction techniques are applied to the same seismic section (A–A').

When depth to detachment is concerned, area balance with bed – length conservation technique produced the deepest estimate for the detachment depth (9.37) Km, whereas constant–slip model produced the shallowest depth (6.6) Km. The flexural–slip, vertical shear and modified Chevron methods produced relatively close results (Fig.11), but the inclined shear produced a shallower depth. Moreover, as far as the predicted fault geometry is concerned, construction techniques used here produced relatively similar fault profile at shallow depths (less than 2 Km), but they produced somewhat different geometries at deeper levels. Therefore, the geometric construction models cannot provide unique answers about the geometry of a listric normal fault at depth and the corresponding detachment depth if seismic and well data are lacking or of poor quality. Withjack and Peterson (1993) suggested that structural interpreters can use fault–prediction modeling to define a range of possible fault shapes and detachment depth and, then using principles of mechanical stratigraphy decide the most likely shape and detachment depth.

In the case of the seismic section (A-A'), excluding the unlikely constant slip model, the constructions show that the listric fault soles at a deep level (7.3 to 9.3) Km, irrespective of the technique used. Based on the C.G.G.'s (1974) aeromagnetic survey, the depth of the basement is estimated to be between (7–10) Km at the area where the seismic section (A-A') is located. Accordingly the fault may sole at the sedimentary cover-basement contact at this particular section. However, the author expects a deeper detachment level at the central inverted parts of the graben.

ACKNOWLEDGEMENT

The author whishes to express his appreciation to the Oil Exploration Company for providing the seismic data used in the study.

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