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Structural Analysis of the Ranikot Anticline, Southern Kirthar Fold Belt, Pakistan

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Abstract

In this paper, different applications of stereographic projections are utilized for the structural analysis of the Ranikot anticline. Structural data of Ranikot anticline from Southern Kirthar Fold Belt of Pakistan is used to construct different diagrams such as beta-diagrams, pi-diagrams and contour diagrams. These diagrams are used to visualize the inter-limb angle, plunge and trend of fold axis, dip and strike of axial surface, fold symmetry, vergence and principle stress axes. This study shows that studied anticline is nearly N-S trending, open, shallow to horizontal, asymmetrical, and east-vergent anticline. Principle stress axis σ1 and σ2 lie in profile plane while σ1 and σ3 lie in axial surface.

Keywords: Structural Analysis, Ranikot anticline, Southern Kirthar Fold Belt, Pakistan

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Introduction

This paper describes the different applications of stereographic, equal area, lower-hemisphere projection to understand the structural geometry of Ranikot anticline. These projections are widely used since 1950s and provide a simple and quick method to represent three-dimensional structural data on two-dimensional stereograms (Marshak and Mitra, 1988). Structural data is plotted on the overly (hereafter stereogram) of stereographic projection and different diagrams are constructed such as beta-diagrams, pi-diagrams and contour-diagrams. These diagrams are used to visualize and calculate the different geometrical aspect of any geological structure. During this work, these diagrams are used to calculate the mean structural attitude of anticline in each studied section, inter-limb angle, plunge and trend of fold axis, dip and strike of axial surface, fold symmetry, vergence and principle stress axes. These diagrams are also used to visualize the structural variation of the anticline. This structural data has wide application in the exploration as well as academia. Plunge and trend of fold axis, dip and strike of axial surface and inter-limb angle are used to accurately locate the structural trap for hydrocarbon in the subsurface. Fold vergence, symmetry and principle stress axes help to understand the direction of deforming forces and regional stress field. Inter-limb angle values also help to understand the intensity of deformation at different locations of the structure. Data of plunge and bearing of the fold axis is utilized to correlate the anticline with regional tectonic features. The results allowed anticline to be understand in relation to regional tectonic perspective and stress fields, thereby improving structural understanding of the region and highlighting the regional geodynamics.

Ranikot anticline is a renowned location for different geological studies in Pakistan. It is N-S trending anticline that runs along the meridian 68º between parallels 25º, 40′ N to 26º, 30′ N, and is located in southeastern front of Kirthar Fold Belt **(Fig. 1).** The Kirthar Fold Belt is developed due to the transpressional collision of Indian Plate with Afghan Block along Ornach-Nal and Chaman fault system during Paleocene/Eocene and Plio-Pliestocene. This fold belt is located in the western half of Lower Indus Basin and extends from the Quetta Syntaxis in the north to offshore Murray Ridge in the south (Kazmi & Jan, 1997). Southern Kirthar Fold Belt is named as "Karachi Arc" by Sarwar and DeJong, (1979). Southern Kirthar Fold Belt is 200Km long and 50Km wide area between Karachi and Sehwan cities of Sindh (Kazmi and Jan, 1997). It consists of series of parallel to sub-parallel, N-S trending en echelon anticlines (Sarwar and De Jong, 1979; Kazmi and Jan, 1997; Schelling, 1999). Ranikot anticline, Badhra anticline, Bhit anticline, Lakhra anticline etc are some of the prominent structures of the Southern Kirthar Fold Belt. The Ranikot anticline is more than 100Km long and can be traced between Sehwan and Thano Bula Khan Cities of Sindh Province, Pakistan. The anticline consists of sedimentary rocks of Cretaceous and Cenozoic ages along with a few basaltic flows within the Khadro Formation of Danian age. The rocks are highly deformed, weathered, eroded and incised by ephemeral water channels. The structural geometry of the Ranikot anticline is obscure and no significant analytical work has been done previously. Furthermore, the stereographic projections are rarely been used to understand the structural geometries of the Southern Kirthar Fold Belt. The only known work in this regard is Brohi et al. (2014), who worked on the structural analysis of the Rois anticline.

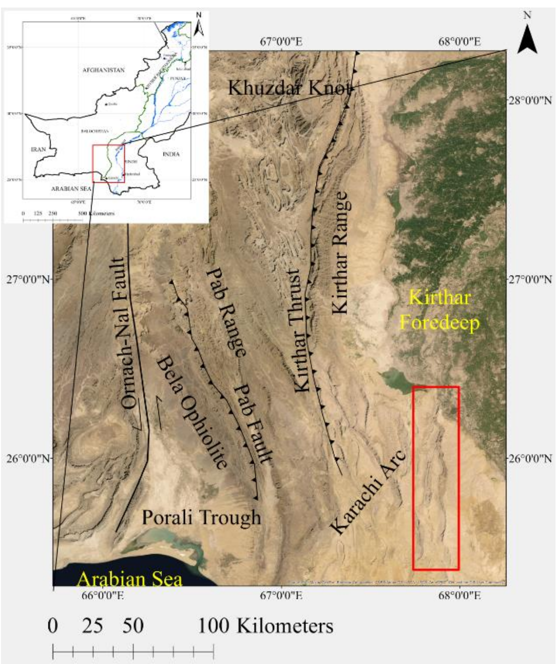

Figure 1: Map of part of Pakistan, showing location of Ranikot anticline in red rectangle and surrounding structural architecture (modified after Hunting Survey Corporation, 1960; Sarwar and De Jong, 1979; Kazmi, 1979; Kazmi and Rana, 1982; Bannert et al., 1992) (Image Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User community)

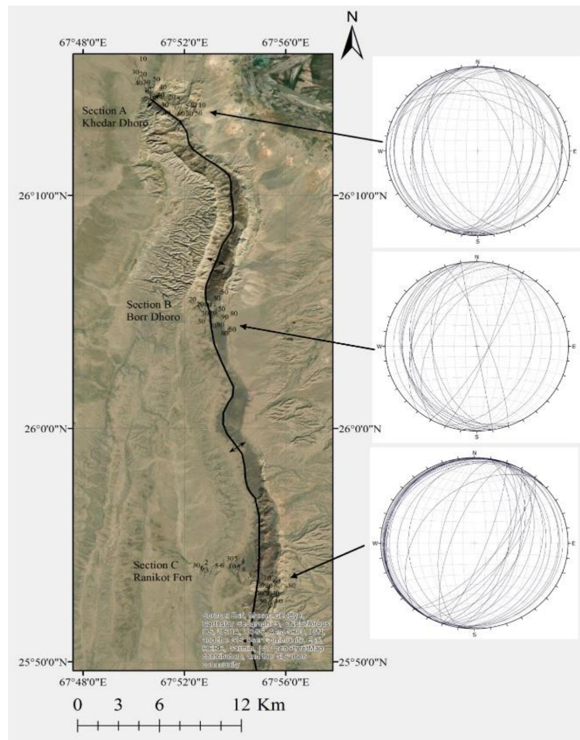

Figure 2: Satellite image of Ranikot anticline, showing the studied sections. Beta-diagram of each section is placed against it. (Image Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Materials and Methods

Three sections are selected for detailed fieldwork and collection of structural data. Dip and strike values are measured at more than 20 different localities in each section to gain good structural control of the anticline. The values of dip and strike are plotted on the satellite image of the anticline using ArcGIS software, thus map generated gives a clear visualization of structural diversity of the anticline **(Fig. 2)**. This structural diversity become very clear when dip and strike values are plotted on the stereogram to construct beta-diagrams of each section. During this work lower hemisphere of Schmidt net is used to analyze data. The methods of plotting structural data on the Stereonet overly are well explained by Billings, 1972; Marshak and Mitra, 1988; Ragan, 2009.

Results & Discussion

Beta Diagram

This diagram is constructed by plotting the plane on the stereogram. Use of beta-diagram to represent bulk data sets of dip and strike gives a clear picture of variation in structural attitude. In this work beta-diagrams are divided into two types. First type is named as composite beta-diagram, which is constructed by plotting each section’s planar data sets on a stereogram. The Composite beta-diagram of each section is placed in **Fig 2** against the respective section to understand the variation in structural trend. In these diagrams, a dip of 0º is plotted on the primitive, and 90º is plotted on the center (Marshak and Mitra, 1988). Therefore, steeper dips tend to be close to the center, and gentle dips close to the primitive. Fold symmetry can easily be understood from beta diagrams. In asymmetrical folds, steeper limbs face the direction of fold vergence. Hence, beta diagrams are useful to determine the regional transport direction of deforming forces.

The second type is here named as mean beta-diagram, which shows the mean structural attitude of a fold at selected section. Mean structural attitude is calculated by plotting vector contours of the poles to planes. The contour of maximum concentration of poles on either sides of stereogram is considered as mean poles of the planes. The mean planes were than plotted against mean poles to construct mean beta-diagrams. Inter-limb angle, plunge and trend of fold axis, dip and strike of axial surface, fold symmetry, vergence and principle stress axes are calculated from these mean beta-diagrams. The results of these mean beta-diagrams were compared with field observations to validate them. Figure 3 shows the mean beta-diagram of each section and their results are tabulated in Table. Construction of mean beta-diagram is hypothetical approach employed during this work. Such technique not exists in the available literature and data. Previously, calculations of structural data were done on the basis of beta-diagram that contains only two planes.

The data of these planes is measured on either sides of fold. But such calculations are not accurate because value of dip and strike varies from place to place. Calculation of different structural aspects on beta-diagram that contains many planes is cumbersome method. Because a beta-diagram according to formula n (n-1)/2, for example contains 20 planes, the number of plane intersection would be 190. Hence such diagrams become cluttered with lines and intersections and it is difficult to interpret those (Billings, 1972). Furthermore, determination of principle stress axis on the stereonet for compressional regimes, especially for folds is rarely attempted previously. Therefore, an attempt is made to determine the principle stress axis during this work.

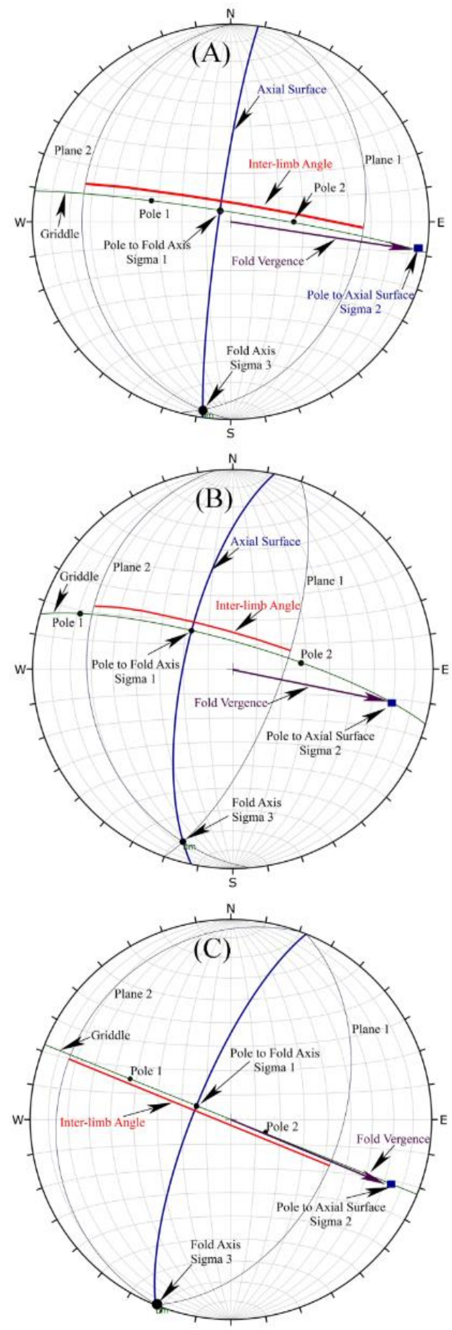

Figure 3: Figure showing the mean beta-diagrams of studied sections of Ranikot anticline, (A) Section A; (B) Section B; (C) Section C.

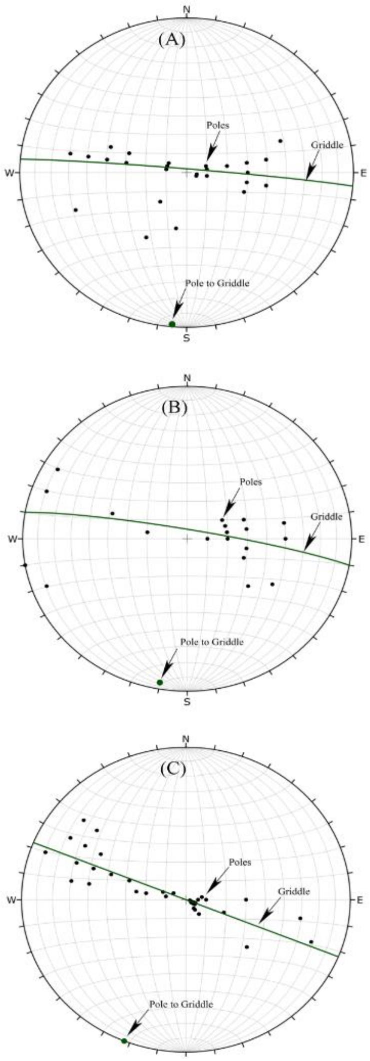

Figure 4: The pi-diagrams of studied sections of Ranikot anticline, (A) Section A; (B) Section B; (C) Section C.

Inter-limb Angle

Inter-limb must be calculated in a plane that is normal to the fold axis as well as oppositely dipping planes. In structural geology this plane is called profile plane (VanDerPluijm and Marshak, 2004). Therefore poles to both oppositely dipping planes and fold axis are plotted, and a great circle is drawn by joining these three poles. This great circle is called either best fit circle or griddle, where bulk pole data sets are plotted. Griddle is the projection of profile plane on the stereogram. The inter-limb angle is measured along this great circle **(Fig. 3)**. It is observed during fieldwork that dip is horizontal to gentle at fold axis, steeper near the inflection line and gentle farther. Furthermore, the inter-limb angle is not uniform geometric angle practically, but it varies from place to place along strike as well as dip direction. Inter-limb angle gives the intensity of deformation as smaller the angle, greater the intensity of deformation (VanDerPluijm and Marshak, 2004). Inter-limb angle of Ranikot anticline at Section A is 120º **(Fig. 3A; Table 1)** at Section B is 85º **(Fig. 3B; Table 1)** and at Section C is 120º **(Fig. 3C; Table 1)**. Folds with inter-limb angle between 60º to 120º are classified as open folds by VanDerPluijm and Marshak (2004); hence Ranikot anticline is an open fold. Inter-limb angle values indicate that deformation intensity is maximum at the section B and decreases north and south of it.

Plunge and Trend of Fold Axis

Fold Axis on the stereogram is obtained where two oppositely dipping planes intersect with each other. This intersection is called Beta (β) (Billings, 1972). Plunge of fold axis at section A is 4º that trends 188º or S8ºW **(Fig. 3A; Table 1)**. Plunge/trend of fold axis at section B is 11º/196º or 11º trending S16ºW **(Fig. 3B; Table 1)**. Fold axis is horizontal at section and it trends 200º or S20ºW **(Fig. 3C; Table 1)**. According to the classification of by VanDerPluijm and Marshak (2004), Ranikot anticline is classified as shallow to horizontal fold. Plunge values of fold axis of Ranikot anticline shows that hinge of the anticline plunges in the southern direction. This indicates that deformation decreases from north to south. Furthermore, trend of the fold axis is nearly parallel to the regional structural architecture, particularly Ornach-Nal fault (**Fig. 1**). Ornach-Nal fault is a transpressional boundary between Indian Plate and Afghan Block (Kazmi and Jan, 1997). Therefore, it can be interpreted that, this anticline is generated due to the compressional forces generated at the Ornach-Nal plate boundary.

Dip and Strike of Axial Surface

The surface that contains all the hinge lines of folded layers is called axial surface (VanDerPluijm and Marshak, 2004). Usually it passes from the fold hinge and divides the folds into two parts. As it passes from all the hinges of folded layers, hence pole to the fold axis is plotted on the stereogram. Then axial surface is plotted as great circle by connection the fold axis and its pole. Dip and strike of the axial surface is very important in the classification of folds. Folds are classified on the basis of angular relationship between enveloping surface and axial surface (VanDerPluijm and Marshak, 2004). Enveloping surface is obtained, when series of folds is available. In case of single fold a median surface is used, which is usually a horizontal surface or a surface that passes through the inflection lines of oppositely dipping limbs. If the enveloping surface or median surface and axial surface are perpendicular to each other, then fold is said to be symmetrical fold (VanDerPluijm and Marshak, 2004). Horizontal surface is used as median surface in this study. On the stereogram, this median surface coincides with primitive of the stereographic projection. Any perpendicular plane to primitive must passes through the centre of projection. But, **Fig 3(A, B and C)** show that axial surfaces of all the sections do not pass through the centre. Hence they are dipping at certain degrees as shown in Table 1. When axial surfaces are not perpendicular to median surface, fold is said to be asymmetrical (VanDerPluijm and Marshak, 2004).

Concept of symmetry of fold and vergence is related with each other. Dip and strike of axial surface is the basis for determining the fold as either symmetrical or asymmetrical as discussed above. Fold symmetry can also be understood from composite beta-diagrams. Fold vergence is the direction of force involved in the development of asymmetrical fold (Compton, 1962; Bell, 1981). Fold vergence is independent of plunge of fold axis, but it depends upon the trend of axis or strike of axial surface. Fold vergence is always perpendicular to the axial surface, therefore use of azimuth to define fold vergence is clear and unique (Bell, 1981). On the stereogram, pole to the axial surface represent the fold vergence, because pole is always perpendicular to its plane **(Fig. 3 A, B and C, Table 1)**. Vergence in the symmetrical fold is difficult to determine, because it always depends upon the asymmetry of the fold. Vergence of the Ranikot anticline is shown in Table 1, which ranges between 098º to 112º **(Fig. 3A, B and C)**. This indicates that compressional forces must have acted from western direction particularly between 278º to 292º. The compressional regime in this direction is Ornach-Nal fault **(Fig. 1).** Hence, symmetry and vergence of the Ranikot anticline prove that, this anticline is generated due to the compressional forces generated at the Ornach-Nal plate boundary.

Table 1: Table showing the results of calculations of mean beta-diagram of Ranikot anticline

Structural Data		Section A	Section B	Section C
Fold Axis	**Plunge (Degrees)**	4	11	0
	Trend/360	188	196	200
	Classification	Horizontal	Shallow	Horizontal
Axial Surface	**Dip (Degrees)**	85	70	75
	Strike/360	188	192	200
	Classification	Asymmetrical	Asymmetrical	Asymmetrical
Inter-limb Angle	**Degrees/180**	120	85	120
	Classification	Open	Open	Open
Vergence/360	**Azimuth**	98	102	112
	Classification	East-vergent	East-vergent	East-vergent

Principle Stress Axes

Geological structure is described in terms of three mutually perpendicular principle stress axes. These stress axes are called σ1, σ2 and σ3, with σ1 ≥ σ2 ≥ σ3. These axes are perpendicular to principle planes of stress (VanDerPluijm and Marshak, 2004). A fold contains at least three planes which are perpendicular to each other. Three perpendicular planes in a fold are axial surface, profile plane and enveloping surface. Principle stress axes are here predicted in terms of deformation. Plane with steep dip or line with steep plunge is more deformed than the gentle dip or plunges. Plane that bisects the inter-limb angle into two parts is the principle plane of σ1. This bisecting plane is called axial surface that experience maximum stress during the development of fold. Furthermore, σ1 must be perpendicular to the σ2 and σ3 (VanDerPluijm and Marshak, 2004). Therefore, pole to the fold axis on axial surface represents the axes for σ1, which has steepest plunge as shown in **Fig 3(A, B and C)**. Following compression uplifting is second dominant process during deformation caused by intermediate component of stress σ2. According to VanDerPluijm and Marshak, 2004, σ1 and σ2 must lie on the same plane, which is profile plane in this case. σ2 is perpendicular to both σ1 and σ3, and has shallow plunge. On the stereogram σ2 coincides with pole to axial surface or fold vergence **(Fig. 3 A, B and C)**. Principles stress axis σ3 is the minimum stress component that acts on the profile plane and hence is parallel to the fold axis. It has shallowest plunge as indicated in **Fig 3(A, B and C)**.

Pi-Diagram

Normally beta-diagrams are used to analyze fewer data sets. In case of bulk data sets, pi-diagram is more convenient (Billings, 1972). Pi-diagrams are constructed by plotting the poles to the planes. The line on stereogram, where poles lie is called griddle. Griddle may be either straight line for non-plunging fold axis or curved for plunging fold axis. Griddle for the poles to the planes gives the plane perpendicular to fold axis. This plane is helpful to select the line of section for construction of geological cross section. In case of scattered poles, griddle is drawn in such a way that the number of poles should be equal or nearly equal on both sides of it. Pole to the griddle gives the plunge and trend of fold axis. If griddle passes through the centre of diagram, it indicates the horizontal fold axis.

Poles on the primitive indicate the vertical bedding and on the centre indicate the horizontal bedding. The uses of pi-diagrams are similar to that of beta-diagrams. They are easy to construct and interpret. But knowledge of beta-diagram interpretation is fundamental to interpret pi-diagrams. Pi-diagrams of studied sections of Ranikot anticline are shown in **Fig 4 (A, B and C)**. These diagrams indicate the orientation of griddle and fold axis is similar to that of mean beta-diagrams. Other geometrical aspects such as inter-limb angle, dip and strike of axial surface, fold symmetry and vergence and principle stress axes are not calculated in the pi-diagrams here, but they can be calculated in a similar way to that of beta-diagrams.

Contour Diagram

Contour diagrams on the stereographic projection are constructed to visualize the concentration of either plane intersections or poles to the planes. Contour diagram that consists of intersection of planes is called intersection contour diagram. Intersections of planes in the beta-diagram are marked on the stereogram and then contours are drawn. Intersection contours gives the plunge and trend of fold axis. Contours near the primitive of stereogram indicate the gently plunging fold axis. On the other hand intersection contours concentrated at the centre of stereogram indicates the vertical fold axis. Intersection contours concentrated between the centre and primitive gives the plunging fold axis. Plunge and trend of fold axis can easily be measured from these concentrated contours. **Fig 5(A, B and C)** shows that concentration of intersection contours is located on the same azimuth of stereogram as that of fold axis on mean beta-diagram.

Contour diagram that shows the concentration of poles to the planes are called vector contour diagrams. Contours of poles to gently dipping planes are concentrated near the centre of stereogram and contours of poles to steeply dipping planes lie near the primitive of stereogram. Vector contour diagrams indicated that anticline has steep eastern limb and gentle western limb. **Figure 5(D, E and F)** (Section A, B and C respectively) shows the vector contour diagram of each studied section of Ranikot anticline.

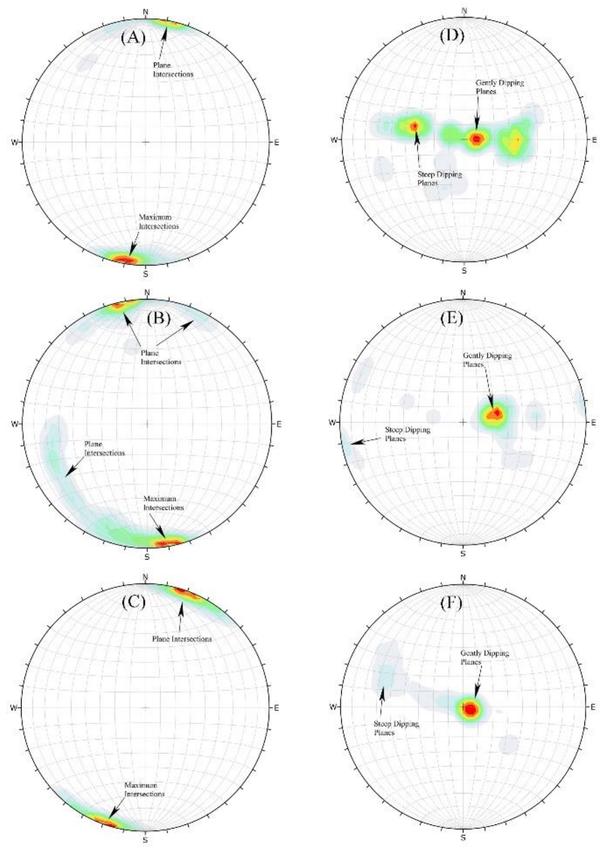

Figure 5: The contour-intersection and vector contour diagrams of the Ranikot anticline.

Conclusions

During present work, structural applications of stereographic, equal area, lower-hemisphere projection are utilized to analyze the structural geometry of Ranikot anticline from Karachi Arc, Pakistan and following conclusions are drawn:

- This study concluded that Ranikot anticline is nearly North-South trending, open, shallow to horizontal, asymmetrical, east-vergent anticline that developed due to compressional forces from Ornach-Nal transpressional fault
- Principle planes of stress are axial surface, enveloping surface and profile plane. Principle stress axis $\sigma1$ and $\sigma2$ lie in profile plane while $\sigma1$ and $\sigma3$ lie in axial surface

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