An Analysis of Deformed Strata in the Paleocene Fort Union Formation near Ekalaka, Montana

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Introduction

The Fort Union Formation of eastern Montana, southwestern North Dakota, and northwestern South Dakota is a sequence of Paleocene fluvial sedimentary strata that are mappable and stratigraphically continuous regionally. There is, however, an unexplained unconformity and a deformed horizon at the base of the Tongue River Member of the Fort Union Formation (see Belt, figure 1, Workshop report, this volume) in Carter County, Montana. The deformed horizon is principally characterized by 1) both sub-horizontal beds and beds dipping as much as 80°, 2) micro-faults with displacements of centimeters and large detachment faults with displacements greater than 10 m, and 3) rare folds with wavelengths from 5 to 15 m. Where the deformed horizon is exposed over a large area, differentiated fault blocks, separated by listric normal faults, can be recognized. Deformation of this type was first recognized by Garrett (1963) near Miles City, MT, 100 mi northwest of our field area.

This project addresses the geometry, origin and cause of the deformed horizon. Is the horizon the result of a series of separate local failures or a single regional event? If there are multiple sub-horizontal detachments, what are their relative directions of extension? Other issues being questioned are the role pre-deformation topography, if any, may have played, and whether a down-cut channel providing a free-face was necessary and/or sufficient for deformation of this kind. Two working hypotheses of the project are that 1) the deformation and the unconformity are directly related to possible regional tilting due to the uplift of the Black Hills, in northwestern South Dakota (Belt, et al., 1992) or 2) that the deformation is the result of slumping of over steepened river channel banks, a mechanism proposed by Garrett (1963).

Field Methods

Based on field observations, the deformed horizon can be characterized by two separate, generalized, geometries. In the first, bedding is sub-horizontal and displaced by oppositely dipping conjugate extensional micro-faults (figure 1). A typical micro-fault is one that can be traced with confidence for 1-2 m and exhibits displacement of 1-10 cm. The second deformed geometry contains dipping beds that are offset by a single set of dipping extensional, card-deck style micro-faults (figure 2). Two things were noted about this second geometry. First, at some outcrops a larger fault, either sub-horizontal or dipping up to 30°, is exposed at the base of the outcrop. These larger faults, traceable through the outcrops and with displacements (probably much) greater than 5-10 m, are believed to be the boundaries of distinct slump blocks. Second, beds and faults either dip in the same direction or opposite directions, but in general the averages of bedding and fault poles at each outcrop lie roughly on the same great circle. While the two generalized geometries were not commonly exposed at a single outcrop, they were always present on the same ridge (except at Airstrip ridge).

Data were collected in the form of strike and dip of bedding and fault planes. Sense of slip and amount of displacement were noted where possible for fault offsets. Trend and plunge of fold axes were measured, although few occur. Geometric relationships between faults and between faults and bedding were recorded. Pairs of intersecting faults were deemed to be especially useful. Outcrops in which at least three or four micro-faults and bedding could be observed and measured were considered to be useful to this analysis. In general, outcrops were located near the top of resistant sandstone ridges and have been grouped into five sites that will be informally referred to as Walt's Surprise Ridge, Baby Emily Ridge, Harrington Ridge, Heggen Ridge, and the Airstrip Ridge (figure 3).

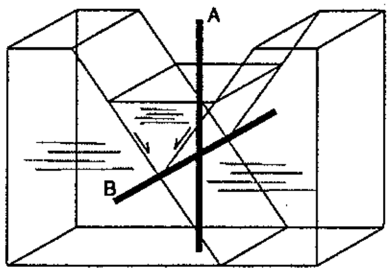

Figure 1. Block diagram showing the general geometry of outcrops exhibiting conjugate extensional faults and sub-horizontal bedding.
A - bisector of the acute fault angle.
B - intersection of the two fault planes.

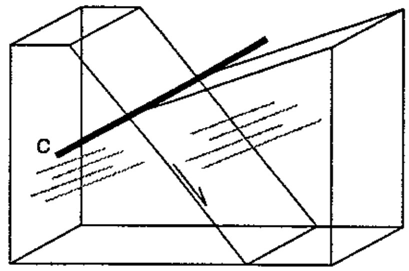

Figure 2. Block diagram showing the general geometry of outcrops exhibiting one set of faults and oppositely dipping bedding.
C - intersection of bedding and fault planes

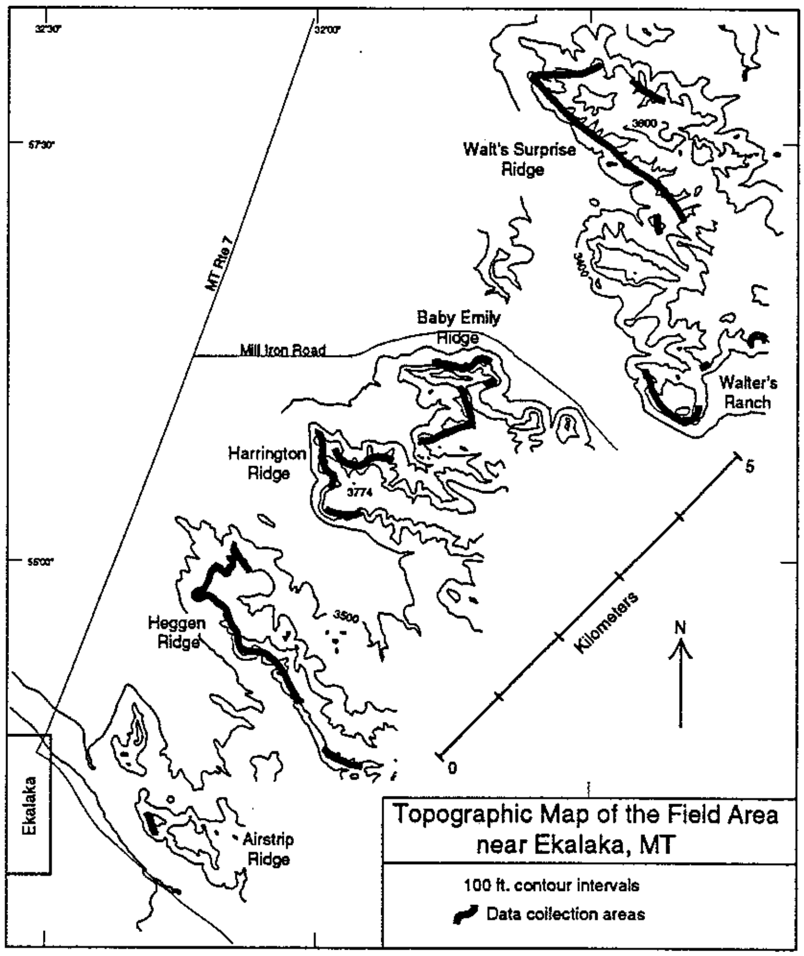

Figure 3. Map of the field area showing the division of sites and continuity of outcroppings.

Analysis and Interpretation

To determine the principle strain axes for the single set of conjugate faults on Walt's Surprise, Baby Emily, Harrington, and Airstrip ridges Anderson's (1972) model for plain strain was applied. In this model oppositely dipping normal faults are expected to strike perpendicular to the direction of the greatest relief of pressure. The greatest pressure is expected to bisect the acute angle between conjugates.

Three average lineations were determined for each ridge. The first were bisectors of the acute angle between conjugate pairs (figure 1). Three of the averages are within ten degrees of vertical and the other two are within 15 degrees of vertical (figure 4). According to Anderson's (1972) model these average bisectors should represent the σ_1 strain axis for each ridge. The average intersection of conjugate fault planes (figure 1), and of fault and bedding planes (figure 2) were determined. For Baby Emily Ridge and Walt's Surprise Ridge these two averages plot within about ten degrees of each other. The average of the fault-fault and fault-bed intersection lineations for each of these ridges was interpreted as the σ_2 strain axis. There is no data from the Airstrip Ridge showing the fault-bed geometry, so the average of the conjugate intersections is interpreted as the σ_2 strain axis (figure 4). The conjugate intersections along the Harrington Ridge are very consistent, but the fault-bed intersections show no trend at all. The decision was made to use only the conjugate intersection average as the σ_2 strain axis at Harrington Ridge. For each ridge the interpreted σ_3 strain axis is plotted perpendicular to the other two axes (figure 4).

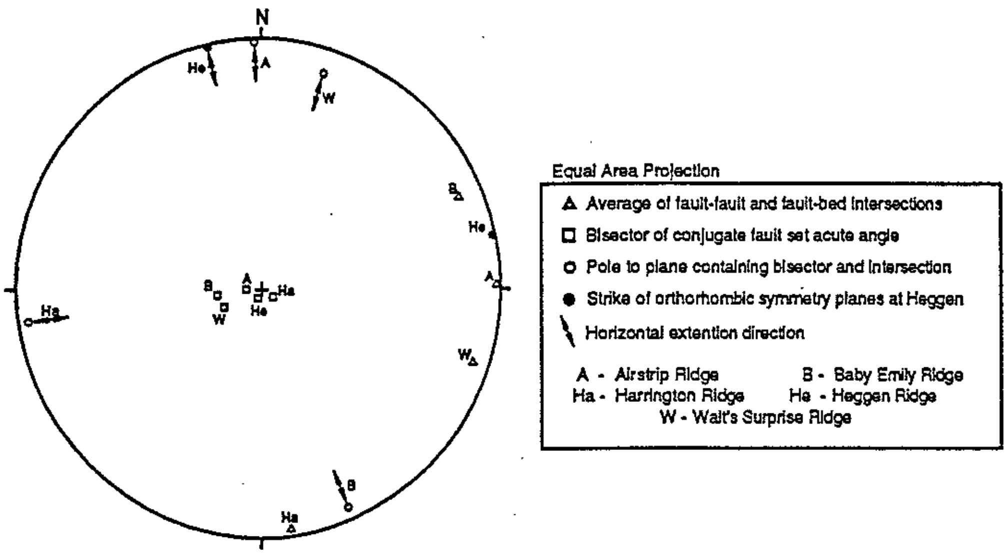

Figure 4. Stereonet of lineations plotted for each site. Interpretation of stress ellipse: 1) The bisectors of conjugate fault acute angles are σ_1 axes. 2) The average of fault-fault and fault-bed intersections are σ_2 axes. 3) Poles to planes containing a bisector and intersection are σ_3 axes and are labeled with horizontal extension directions.

The stereonet of all conjugate geometry poles to faults on the Heggen Ridge shows four clusters of poles. A density plot confirmed the observation that there are what appear to be two separate sets of conjugate faults along the Heggen Ridge. These two sets of conjugates are not geographically separated. Krantz's (1988) odd-axis model provides a method for interpreting multiple sets of coeval conjugates and was applied to the Heggen Ridge data. This model predicts orthorhombic symmetry for the multiple conjugate sets. While the symmetry of the Heggen Ridge structures is not perfect, it was sufficiently close to orthorhombic to allow some interpretations to be made. The principle stress axes have been interpreted as the "best fit" symmetry axes of the structures. (figure 4).

Because all of the orientations of σ_1 axes are so close to vertical, gravity appears to be the principle positive strain on the system.

Conclusions

The minimum stress direction was sub-horizontal and within 20 degrees of a North-South axis for Walt's Surprise, Baby Emily, Heggen, and the Airstrip ridges (figure 4). The Harrington ridge appears to have experienced a reversal of the intermediate and minimum strain directions. The difference between the absolute magnitudes of maximum and minimum principle strains is not known. The answer would determine which was the force behind the deformation, a horizontal tectonic pull or gravity.

Such a regional pattern might be explained in a number of ways. Each hypothesis depends on the smectite rich Ludlow Member of the Fort Union acting as the weak layer through which a regional decollement was cut. Field observations that the Ludlow Member is not deformed support this assumption. The hypotheses are; 1) slumping was caused by river canyon wall cave-ins. If so, then a pattern of sub-parallel channels is necessary. This could be achieved with a trellis drainage pattern, usually the result of regional folding of the underlying strata (Press and Siever, 1986). There is no evidence near the field area to support a hypothesis involving regional folding of the Fort Union Formation; 2) slumping was caused by regional tectonism. Possible geometries that might have induced enough regional topography to promote slumping include tilting due to uplift of the Black Hills, slight regional flexure due to compression from the Beartooth and Bighorn thrust sheets, and the formation of a fore-arc bulge in front of the same thrust sheets.

There is a question of geometry whenever slumping is discussed. Generally the slumped block needs a void to fill. If there is no void to fill the toe of the deformed unit must exhibit compressional features (De Jong and Scholten, and references therein, 1973). There is some evidence that there were voids to fill in the field area. There are areas along the Harrington and Walt's Surprise Ridges where channel deposits are found in the deformed horizon (see Cole figure 1). The deposits are coarse conglomerates that contain large matrix-supported blocks of the deformed lithology. Belt (personal comm) believes that these deposits are syn-depositional and were caused by slumping into the channels. In this case the deformation would have been regional, slumping into channels, but with a direction of extension that was not necessarily perpendicular to the channel as would be expected with normal channel bank cave-ins.

References

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