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Qualitative Interpretation on Deformation of Geological Structure by Cross–Section Restoration: Application to Overturned Fault–Bend Fold

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Summary

There are many fault–related folds in anthracite fields of DPRK and some of them are the overturned fault–bend folds. It is a matter of great significance to clarify the deformation character of such folds in explaining the distribution of coal seam. Interpretation of deformation, based on cross–section restoration, is done in a way that finds out inverse deformations by restoring sections across tectonic structures to the initial horizontal states and then obtains information about the present–day state of such structures. Strains are marked by parallelograms with good visual quality instead of traditional strain ellipse. This technique applies to two kinds of fault–bend folds: one is an overturned parallel fold and the other one is an overturned similar fold. In case of the former, layers are deformed in the same directions and strain intensity is the largest in the overturned limb. In case of the latter, strain in the hinge zone is the weakest, strain direction is from both limbs towards hinge zone and strain intensity is still the largest in the overturned limb.

Keywords: fault–related fold; overturned fold; interpretation of deformation; parallel fold; similar fold; cross–section restoration

1. Introduction

Study on the geological structure has the great significance theorically and practically because it plays the important role in finding out geological composition and distribution law of resources in the research region. Hence many researchers have done studies on formation, evolution and internal strain of geological structures. Especially studies on the fault–related fold [4, 12, 13, 19, 22, 25, 33] have become a trend last few decades. Fault–related fold is a fold formed during faulting and it can be created all under either tensile or contractional condition. Fold related to tensile faulting is rollover fold and folds related to contractional faulting are divided into the detachment fold, the fault–propagation fold and the fault–bend fold, according to the developing stage of thrust. Studies on fault–related fold can be largely classified into restoration and modeling [2, 6, 9, 17, 28, 32, 36, 37], geometric analysis [8, 15, 35], interpretation of internal strain [5, 20, 31], etc. Most of studies were focused on normal folds which are also parallel folds and about overturned fold it was only discussed formally.

There are many overturned fault–related folds in anthracite fields, DPRK. Clarifying deformation character of such folds is significant in explaining the distribution of coal seam because geological structure affects distribution of coal seam. Previous methods of measuring deformation of geological structures include evaluation by softwares for stress analysis [34], direct measurement by various markers [3, 20], method based on the balanced cross–section [5, 14, 24, 27], etc. Among them method based on the balanced cross–section draws the attention of geologists because deformation can be simulated on the basis of the given exploration data without special field work. Especially method to simulate deformation using cross–section restoration [24] is relatively simple and quantitative method that interprets strain states of present–day cross section from inverse strain ellipse by developing previous studies [10, 11, 16, 26, 29] based on restoration technique. In this paper we are going to simulate deformation of the overturned fault–bend fold by employing this technique. However, in the paper we do only qualitative interpretation by using parallelogram instead of strain ellipse because quantitative interpretation is not particularly needed in finding the relationship between the geological structure and the distribution of coal seams. For this, Okdong area with two kinds of overturned fault–bend folds is selected in anthracite field, DPRK. One is a parallel fold and the other one is a similar fold interbedded into two parallel folds. Main purpose of the paper is to confirm possibility whether we can apply technique to simulate deformation using cross–section restoration to arbitrary fault–related fold by observing the strains in overturned parallel fold and overturned similar fold.

2. Methodology

The methodology presented in this paper is fundamentally equal to that suggested by researchers [24]. It only improved visual quality using parallelogram which shows angular shear strain instead of strain ellipse as strain marker.

Principle of method to simulate deformation using cross–section restoration is as follows (Fig. 1). Suppose strain of deformed geological structure in present–day geological cross–section as initial state that strain is zero (Fig. 1.a). Restore this cross–section to original state based on the principle that primary attitude of sedimentary cover is horizontal and measure strain in each part of beds (Fig. 1.b). Because restoration of geological structure is inverse process of resultant deformation undergone from original state to present–day state, changing a shape of strain marker in the opposite direction represents an actual strain that part underwent (Fig. 1.c). Overlapping these changed strain markers onto the present–day, deformed geological cross–section (Fig. 1.d), and deformation character in each part of the geological structure can be interpreted on the whole.

In a word, this method is a technique to judge the present–day, deformed state from deformation estimated through cross–section restoration.

Processes to simulate deformation based on cross–section restoration are as follows.

First, Construct a geological cross–section parallel to the tectonic transport direction, partition into parts with similar deformation and overlap the squares with suitable size onto each part of beds.

Second, Restore the cross–section and construct parallelograms on the basis of the deformed amounts in every part.

Third, Change shapes of parallelograms conversely and overlap them onto corresponding parts of the present–day, deformed geological cross–section.

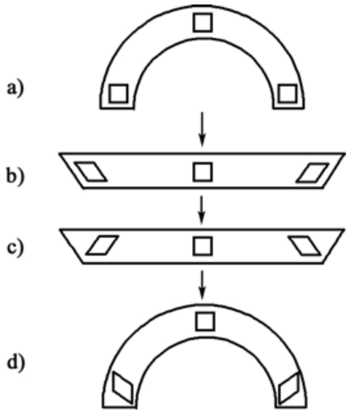

Figure 1. Diagram of deformation simulation using cross–section restoration

Strain marker used in the process is parallelogram. The angle between a normal line of a square and an oblique line of a parallelogram is the angular shear strain ψ. The angular shear strain ψ is estimated from angle that the vertex is nodal point of lower bed surface in each part of the present–day, deformed cross–section and two end points are a corresponding nodal point of upper bed surface and a displaced point by the cross–section restoration. Then shear strain γ is calculated as the follows.

$$\gamma = \tan\psi \tag{1}$$

If necessary, Parameters of strain ellipse can be quantitatively derived from shear strain. The following formulae are for the magnitude of maximum stretch $\sqrt{\lambda_1}$, the magnitude of minimum stretch $\sqrt{\lambda_2}$, the ellipticity R_s, the orientation of the maximum stretch θ and the orientation of the lines of no finite deformation β of the strain ellipse in case of the simple shear strain.

$$\lambda_1 = \frac{\gamma^2 + 2 + \gamma\sqrt{\gamma^2 + 4}}{2} \tag{2}$$

$$\lambda_2 = \frac{\gamma^2 + 2 - \gamma\sqrt{\gamma^2 + 4}}{2} \tag{3}$$

$$R_s = \frac{\sqrt{\lambda_1}}{\sqrt{\lambda_2}} = \lambda_1 \tag{4}$$

$$\lambda_2 = \frac{\gamma^2 + 2 - \gamma\sqrt{\gamma^2 + 4}}{2} \tag{5}$$

$$\tan\beta = \frac{\gamma}{2} \tag{6}$$

Like this, using parallelogram which shows only the magnitude of the shear strain instead of strain ellipse enables us to calculate simply and improve visual quality. It is important to divide geological cross–section reasonably when you apply this method to reality. This method can be simply applied to simulate qualitative deformation of various geological structures that do not need quantitative interpretation in particular.

In the paper, though there is a software package for the construction of balanced cross–sections developed [21], new software was made by Borland Delphi 7 language out of the necessity and its reliability was proved by applying to the fault–propagation fold tested by previous researchers [24] and attaining the same result.

3. Application

In order to test the validity of the method presented, it is applied to the fault–bend folds developed in anthracite field, DPRK.

3.1 Geological setting and construction of a cross–section

Research region is situated in Okdong area, Pukchang County, Southern Pyongnam Province and is southeastern part of Changansan synclinorium, middle coal–bearing concession of Northern Pyongnam Coal Field. Stratigraphy includes Mandal Formation (O_2*mn*) in Popdong Group, Hongjom Formation (C_2*hn*) and Ripsok Formation (C_3*rb*) in Kangdong Group, and Sadong Formation (P_1*sd*), Gobangsan Formation (P_2*gb*) and Taejawon Formation (P_2–T_1*tz*) in Kaechon Group. These Formations contact conformably, disconformably or structurally by fault. Faults are largely divided into Songrim–Wondong fault, Obosogol fault, Okdong–Pomsangol fault and Saebatgol fault from southeast towards northwest (Fig. 2.a). These faults are apparently seen as normal fault or reverse fault but they are all reverse faults. An overturned fold developed in hangingwall block of Okdong–Pomsangol fault indicates that this fault is a reverse and overturned one is also a fault–bend fold. Cross–section was constructed parallel to the tectonic transport direction, based on various geological data (Fig. 2.b). As you can see in Figure 2.b, main rocks are sandstones, siltstones and slates in Gobangsan Formation. Because some of Gobangsan Formation was lost by erosion, the lost part is restored. Then, a sandstone bed in Figure 3b, is restored as a parallel fold and lower Gobangsan Formation (P_1gb_1) is restored as a similar fold (Fig. 3.b).

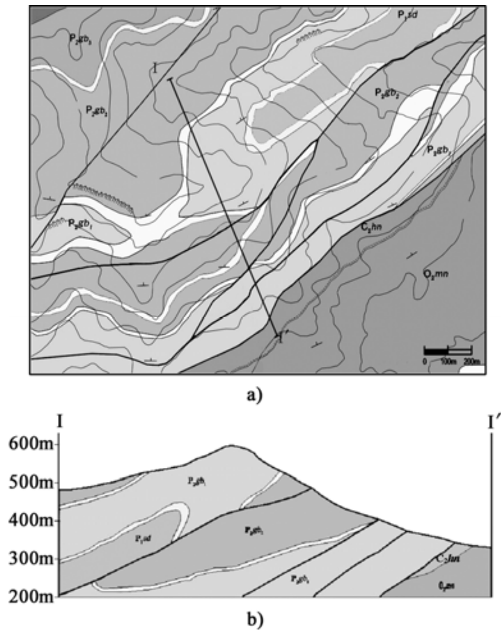

Figure 2. Geological map
a) and cross–section I–I′ b) of research region

3.2 Deformation simulation

We did deformation simulation only for the overturned fold (Fig. 3b) in the hangingwall block of Okdong–Pomsangol fault because deformation is small in the footwall block. Figure 3a and Fig. 3.b show resultant figures in each stage of deformation simulation.

As you can see in Fig. 3.b, deformation is different in beds and also in places in a bed. Deformation is the smallest in a normal limb of Sinchang sandstone, the upper sandstone bed of Gobangsan Formation in Fig. 3.b, and in a hinge zone of lower Gobangsan Formation (P_1gb_1). The largest deformation appears in the overturned limb of Changsan sandstone, the basal bed of Gobangsan Formation in Fig. 3.b. Totally, deformation gets stronger with the depth and deformation in the overturned limb is stronger than that in the normal limb in a folded bed.

In the meantime, strain intensities vary in places in the parallel folds (Changsan sandstone and Sinchang sandstone) but their deformed directions are the same. This result is different from the result of fault–propagation fold tested [24]. The fault–propagation fold tested was the parallel and normal fold, and his result showed that deformations in both limbs converge towards the hinge zone. This suggests that deformation direction in a folded bed depends on either normal fold or overturned fold though the fault–related fold is the parallel fold.

However, Deformation in the overturned limb (forelimb) is stronger than that in the normal limb (backlimb) as in the case of fault–propagation fold.

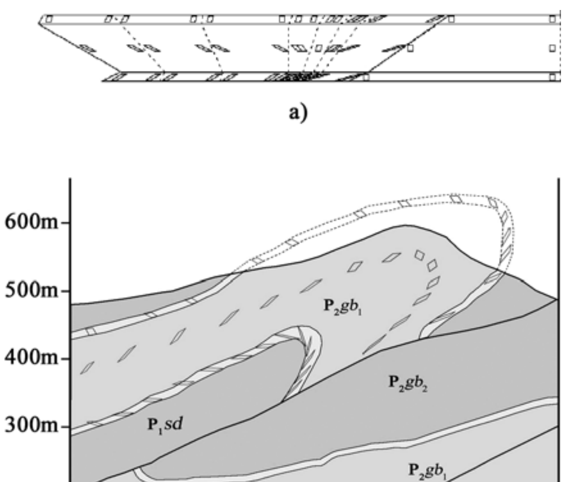

Figure 3. Deformation simulation of the overturned fault–bend folds a) result of cross–section restoration, b) result of deformation simulation

On the other hand, in case of the similar fold (lower Gobangsan Formation, P_1gb_1) deformation in the overturned fold is the same as that in the fault–propagation fold. That is, deformation in hinge zone is the weakest and that in both limbs are done towards hinge zone. This says that materials in both limbs were transported into hinge zone and the similar fold was formed. Finally, this technique explains the mechanism of similar fold, too.

As a result, technique to simulate deformation using cross–section restoration can be applied to the arbitrary fault–related fold.

4. Conclusion

To sum up, we can know that deformation characters in the folded beds depend on the shapes of the fault–related fold. In case of the parallel and normal fold (fault–propagation fold tested by previous researchers [24], the deformations of both limbs are converged towards the hinge zone and deformation in the forelimb is stronger than that in backlimb. In case of the parallel and overturned fold (sandstone beds in research region), the deformation in the overturned limb (forelimb) is stronger than that in the normal limb (backlimb) but the deforming directions are the same. In the case of the similar and overturned fold (lower Gobangsan Formation), the deformation in the overturned limb (forelimb) is stronger than that in the normal limb (backlimb) and the deformations of both limbs are converged towards the hinge zone.

Like this, the method presented in the paper seems to successfully simulate deformation in the arbitrary fault–related fold.

Because this paper focuses on the test to whether this technique can be applied to the overturned fold and the similar fold of fault–related fold, the simulations tested by previous researches [1, 7, 8, 23] were not done. Besides, researchers [14, 18, 30] are suggested that length is not preserved in real cases.

However, as research result shows, I think this technique is a useful method that can be applied to almost all geological structures.

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