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A technique for the analysis of refold structures

RICHARD L. THIESSEN and TERRANCE HAVILAND

Geology Department, Washington State University, Pullman, WA 99164, U.S.A.

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Abstract—When folds of multiple episodes interact, complex interference patterns or refolds result. Simple patterns may be directly interpreted by the structural geologist, but more complex ones are often ambiguous and undecipherable. A technique to analyze many refolds is presented which does not directly require any field measurements of structural data. Instead it requires a series of parallel views through the refold, as can be obtained in mines or from a slabbed rock sample. Individual folds are identified on the level maps and hinge trends and plunges are calculated. Stereonet plots and cross-sections yield the fold orientations and shapes. Assumptions inherent to this technique are (1) the first folds were cylindrical and (2) the second folding motions were approximately those of similar (shear) type folds.

The above technique was applied to a small-scale example from the Kootenay Arc, Washington. Analysis showed nearly coaxial folds of complex en échelon, non-cylindrical and non-similar type characterizing both generations. This example demonstrates that the technique is applicable to refolds that do not meet the idealized assumptions about folds. This technique should prove valuable to geologists working in other refold areas and is particularly applicable to mining problems for which the necessary three-dimensional data are available.

INTRODUCTION

WHEN AN area has undergone several stages of deformation, complex three-dimensional refold shapes can result (Ramsay 1967, Thiessen & Means 1980). One of the main problems in refold classification is that the two-dimensional patterns that a geologist might see on an outcrop or map are not unique (Thiessen & Means 1980, Thiessen in press). In fact, a single two-dimensional flat view of a refold, such as an oval shape, can be quite ambiguous. What a structural geologist needs is a technique to analyze a refold and determine the waveform, amplitude and orientation for each folding episode. One technique has been developed by Carey (1962) and reviewed by Ragan (1973). This method is applicable only to Ramsay's (1967) type 3 (coaxial) refold structures in which the structure is just a complex two-dimensional pattern which is extended in the third dimension. We have developed a method that enables one to analyze type 1 and type 2 refolds (basin-and-dome, and crescent), which in the third dimension are much more complex. However, this method cannot be applied to type 3 refolds and it is complementary to Carey's technique. Neither technique can unravel type 0 (trivial) refolds. These would not be readily distinguished as refolds by the field geologist and so are not considered further.

The technique we present involves locating fold hinges in three-dimensional space. In order to analyze a type 1 or 2 refold, one therefore has to have good three-dimensional mapping control. This type of control can be obtained with a rock sample by cutting the sample into a series of parallel sections, preferably perpendicular to the main structural grain. If the rock sample was oriented when collected, the data obtained can be related to field studies. This sort of three-dimensional control can also be obtained in a mine, where mining levels yield the necessary data on hinge locations. This technique has been successfully applied to both kinds of problems. In this paper, we analyze a single rock sample. In a companion paper (Thiessen & Brown in prep.) we analyze complex folds in a mining zone in northwestern Manitoba.

The sample in question was collected from within the Washington part of the Kootenay Arc, which is distinguished by multiple generations of folding, often nearly coaxial (Mills & Nordstrom 1973). Its field orientation is unknown. It is composed of alternating layers of marble and phyllite, and was cut into ten parallel serial levels for analysis. The different levels of the sample exhibit a remarkable variety of refold patterns including hooks, basins, domes, crescents and bird's heads (Fig. 1). Figure 2 is an interpretation of the level of the refold shown in Fig. 1. The locations of first and second fold hinge points used in the analysis are indicated. Figure 2 also shows the quartz–feldspar boudins (cross pattern) that dominate the lower portion of the sample. Some of these boudins appear to control folds, while others are obviously involved in the folds. In a few locations the phyllite and marble layers are also stretched and necked. This portion of the sample was too complex for analysis.

TECHNIQUE OF ANALYSIS

Hinge planes

This technique must assume that the folds are all cylindrical and that the second folds are similar or shear folds. However, the analysis of our example demonstrates that the technique works very well on more complex fold systems, and in fact actually determines the non-cylindrical and non-similar nature of folds of both generations. Consider the two episodes of folding shown in Fig. 3(a). Both are simple sinusoidal folds. The second folding motions produce similar folds by differential simple shear (particles move along shear planes) and thus interact with the first folds. The movement of point A′ during the second folding motions will cause shear plane 1 to shift to the right, also moving point A and all points along the dashed line shown on the first folds. Similarly, movement of point B′ will shift plane 2 and point B to the left and movement of C′ will shift the third shear plane and point C to the right. When this is accomplished, a three-dimensional refold (Fig. 3b) results. Note that points A, B, and C originally defined a straight line, which was one first-generation hinge. They still lie on the first fold hinge, but it is now curved. Similarly, points A″, B″ and C″ also lie on one folded first-generation hinge. The initially straight first fold hinges are bent into a skewed projection of the second waveform. Each individual hinge is deformed within and defines a single plane. This plane will contain the original f_1 orientation and the second slip orientation (a_2). The plane is herein named the *first hinge plane*. Any cross-section parallel to the first hinge plane (Fig. 3c) would show an oblique view of the second waveform. This is because, for cylindrical folds, the first folds (Fig. 3a) can be thought of as a series of straight lines drawn parallel to the original f_1 orientation. Each of these lines will be folded into a shape mimicking the second fold form, and each will also be contained in one single plane parallel to the first hinge plane. Any section prepared parallel to this orientation will therefore yield data on the second fold form. The orientation of the first hinge plane is obtained in the following way.

The technique used is quite similar to Ramsay's (1967) treatment of a lineation being folded by a similar fold. By plotting the trend and plunge of each small first hinge segment on a stereonet, one can obtain the girdle of points which would represent the desired plane. This can be done in two ways. The first is simply to measure the trend and plunge of each hinge segment observed. The second technique, used here, is to examine a series of parallel levels, such as cut slabs of a rock sample or mining levels. One can select a single first fold hinge that

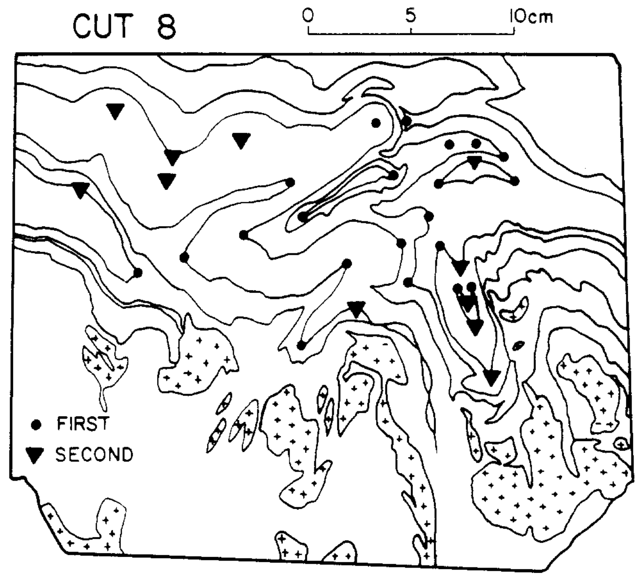

Fig. 2. Interpretation of Fig. 1. The marked hinge points were used in the analysis. Most are on marble/phyllite contacts, but several are on a single phyllitic band within a marble layer. The cross pattern indicates quartz–feldspar boudins.

appears on two different levels, and from trigonometric relations, determine the trend and plunge. Notice that this will give the trend and plunge of the straight line between the two hinge points, which is an approximation of the hinge itself. However, this approximation actually gives the desired result. Since a single first-generation hinge will be folded into a plane, the straight line between any two points will also lie within the plane. Plotting a series of these lines on a stereonet should give the first hinge plane orientation.

This plotting technique is not limited to fold hinges observed on adjacent levels. A line drawn from a hinge location on the first level to the same hinge on the fifth level will also lie in the first hinge plane. A more important example is if a hinge appears twice on one level, such as at the two tip points of a single crescent shape. The line between these points will also lie in the first hinge plane. The trend of this line would theoretically be the strike of the first hinge plane, as long as the viewing level is a horizontal plane. By using hinge locations on widely separated levels or on the same

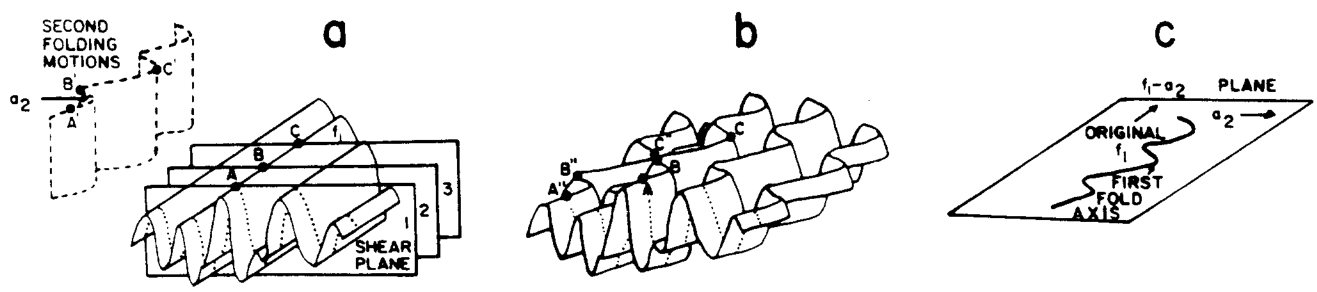

Fig. 3. (a) First folds, shown on the right are affected by simple shear of the second folding motions. Shear planes 1, 2, and 3 contain points A′, B′ and C′ which move as shown in the upper left. The dashed line on the first fold form is the trace of shear plane 1. (b) The three-dimensional refold structure created by the relationships illustrated in (a). Points A, B and C correspond to points A, B and C in (a). Similar points shown on the left hand first-generation anticline are labelled with double primes. (c) The f_1–a_2 plane, defining the first hinge plane. It contains the sinusoidal waveform that the first fold axis has been bent into by the second folding motions.

Fig. 1. Photograph of one level of the analyzed sample, measuring approximately 20 × 30 cm. Notice the refold patterns in the upper portion of the sample and the complexities associated with the quartz–feldspar boudins in the lower portion.

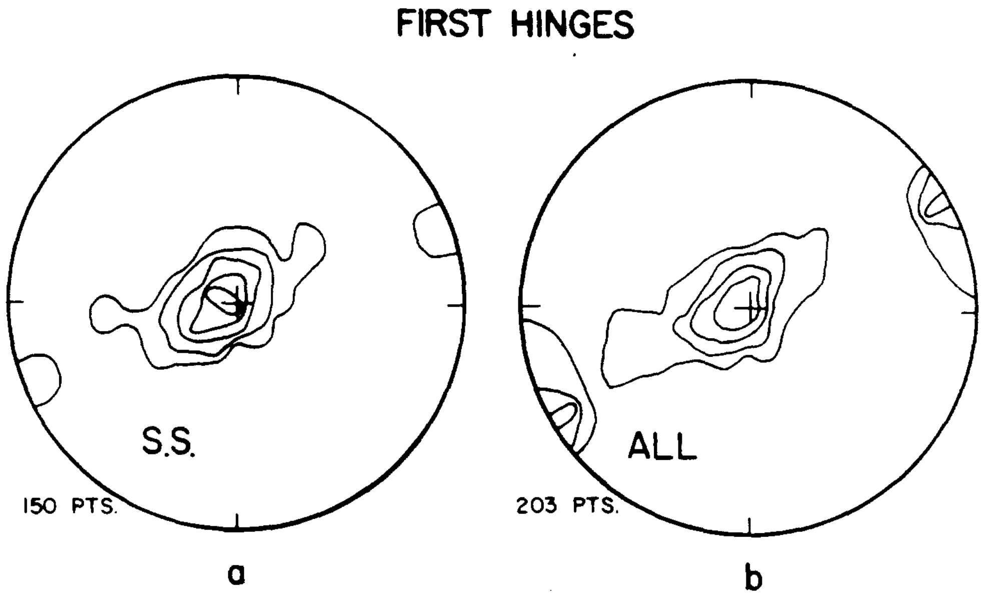

Fig. 4. Lower hemisphere contoured stereonet plots of the first hinge data. (a) Hinge segments between adjacent levels only, defined as single segments (SS). (b) All possible hinge lines. Notice the well defined orientation of the first hinge plane in both cases.

level, one can add considerably more data points to the stereonet plot. As in any structural problem, more data on the net allow for a more accurate determination of the girdle.

Figure 4(a) shows the orientations of the first hinge segments from the sample, calculated from adjacent levels (designated SS for single segments) while Fig. 4(b) shows orientations of lines between all levels. As can be seen, both describe a nearly vertical first hinge plane striking NE.

The next stage of the problem is to obtain the first fold waveform. Each of the shear planes of the second folding episode cuts through and preserves a slice of the first folds (Fig. 3a). Any section parallel to this plane will therefore show some projection of the first fold waveform. For example, the sectional slice of shear plane 1 is shown as a dashed line in Fig. 3(b), and extends through points A and A″. In similar folds of this sort, the shear planes are parallel to the axial planes. This orientation is obvious if the rocks have well developed axial planar cleavage. Carey (1962) states that the axial plane defines and contains all the fold hinges, so the hinge segment technique described above can also be used. However, only second generation hinges should be plotted on the stereonet. The resulting girdle will define a *second hinge plane* which should be the second axial plane. Sections prepared parallel to this should show an oblique section of the first fold waveform.

Figure 5 shows the second hinges. As can be seen, the single segment plot does not define a girdle. One has to add segments between widely separated levels and correlate f_2 hinges across f_1 folds in order to reveal the

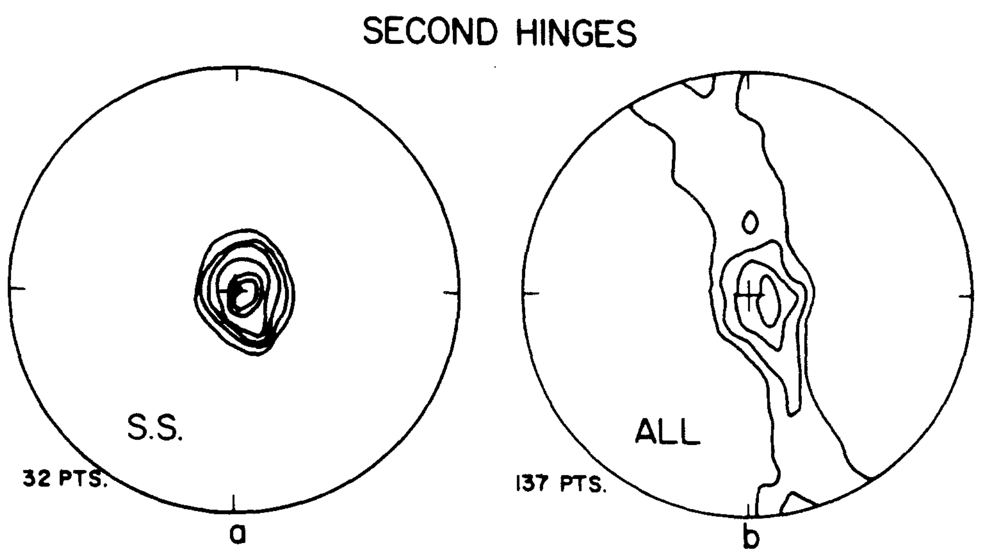

Fig. 5. Second hinge orientation data, presented in the same manner as Fig. 4. Notice that the plot of single segment (SS) data points, (a) obtained from adjacent levels does not define a second hinge plane orientation, whereas the plot of all hinge lines (b) does.

Fig. 6. Locations of five sections parallel to the second hinge plane. The sections dip 85° NE. When these sections are prepared, they show skewed views of the first fold waveform.

second hinge plane. This plane is again nearly vertical and trends west of north. Also notice that the main clusters of f_1 and f_2 hinges are almost coaxial. This relationship was substantiated by local field mapping and is a typical pattern observed in rocks of the Kootenay Arc. However, the sample was acquired as a loose block, so the directions shown in Figs. 4 and 5 do not reflect true orientations.

The advantage of using the hinge segment technique is that one does not have to have any structural measurements in the study area. Maps or photographs of the rock slabs or mining levels are all that are required. This is particularly valuable in analysis of mine workings, where structural data are hard to obtain due to the planar nature of the blasted surfaces. However, if structural data can be obtained, it would enhance the analysis and its predictive value.

Fold waveforms

Following the technique outlined above, deriving the waveforms is simple. Calculate trends and plunges of all possible fold hinges. Plot the first-generation hinges to determine the first hinge plane orientation. Sections parallel to it will show the second folds. Similarly, sections parallel to the second hinge plane will show the first folds. With multiple levels available it is easy to locate and generate a series of parallel sections. The first and second waveforms arrived at by this technique will not usually be the true profile view of the waveform. In general, the sections will not be perpendicular to the fold axes, and so the sections would be skewed. This can easily be corrected for by simple geometric considerations.

Figure 6 shows the locations of a series of sections parallel to the second hinge plane. The cross-sections themselves are schematically summarized in Fig. 7. These show a highly skewed view of the first-generation folds, for which individual hinges are numbered. Notice the complex nature of the folds. Hinge 25 is the dominant hinge for the first three sections, then totally disappears halfway through the refold. Only one hinge, number 20, can be traced clear across the sample. Figure 8 is a cartoon version of what the first folds look like in three dimensions. The complex en échelon nature of the folds is obvious. In fact, there appears to be a zone in the rock where all synforms become antiforms along the fold trend and vice versa.

Figure 9 shows the locations of five sections parallel to the first hinge planes. Schematic summaries of the cross-sections (Fig. 10) show the second-generation folds, which again exhibit complex en échelon, non-cylindrical and non-similar arrangements of individual hinge lines. Figure 11 is a three-dimensional cartoon of these folds.

Once the various folds are identified, their axial planes can be superimposed onto a map of one of the levels (Fig. 12).

Kinematic shear axes

The refold analysis technique described above yields even more specific information about some of the kinematic axes describing the folds (Ramsay 1967, Thiessen & Means 1980). As stated previously, the first

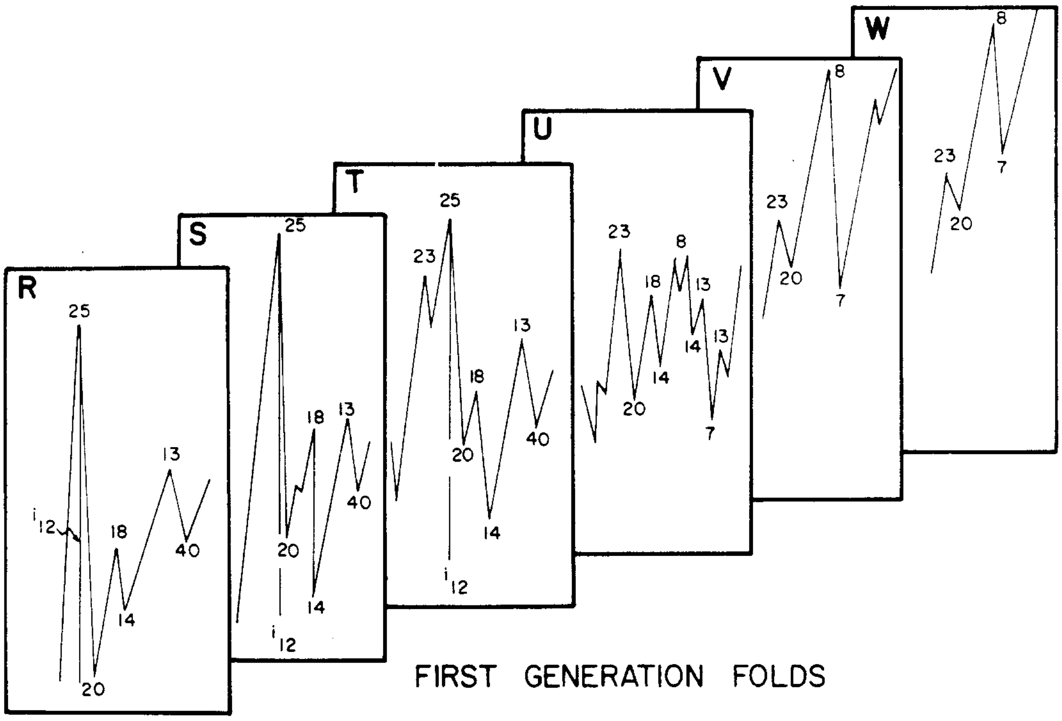

Fig. 7. Schematic versions of the sections located on Fig. 6. Individual first-generation hinges and waveforms are shown and designated with numbers. Notice the complex en échelon character of the folds. Only one hinge (20) extends clear through the refold. i_{12} designates the trace of the first fold axial plane on these sections.

hinge plane contains a_2 and f_1. The second hinge plane is also the second axial plane, and so contains b_2 and a_2, which are mutually perpendicular. The intersection of the first and second hinge planes on a stereonet (Fig. 13) will then give the second slip direction (a_2). The folding motion axis (b_2) will be within the second hinge plane and perpendicular to a_2. The pole to the axial plane (c_2) will also be the pole to the second hinge plane. Thus, the axes that completely define the orientation of the second folding motions are rapidly determined. This technique is analogous to Ramsay's (1960, 1967) technique of determining the a_2 direction by examining first fold hinge lineations as they are folded across a second fold. This is different from most other structural techniques, because in other problems, one is usually dealing with

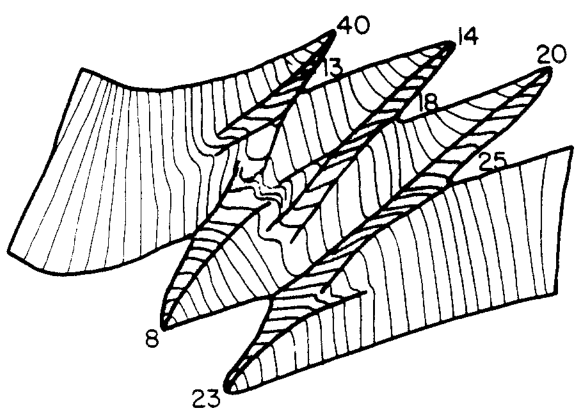

Fig. 8. Three-dimensional cartoon showing a single wall-like layer that has been folded by the first generation folds shown in Fig. 7. The diagram is drawn with lighting coming from the right side, so that hinges 13, 18, 8, 23 and 25 are all antiforms.

just the second generation fold hinges, which are the intersections of the second axial planes with whatever surface is present. In other words, most structural analysis determines only the orientations of the folds produced by the folding motions. Our technique determines the relative motions themselves, allowing for a much more complete analysis of the refold. However, the motions that are determined are constrained by the simple-shear model.

The original orientations of the first fold axes are more difficult to determine. The average post-f_2 folding direction of f_1 is often fairly obvious from the clustering of first hinge measurements (Fig. 4). The second folds would cause the data points to scatter from a single cluster, and if the second folds were ideal chevron folds, two clusters would result, neither representing the original orientation of f_1. The orientation of the first axial plane can be readily measured in the field using axial planar cleavage or observations in hinge zones, but the axial plane would have subsequently been folded. Also, in many cases direct measurement of the axial plane might be difficult. For these reasons, a technique based on the data already available will be presented. Ramsay (1967) described several techniques for determining the original orientation of f_1. The most obvious is simply to measure the first fold hinges in an area that has not undergone significant second-stage deformation. He also showed that, for shear folds, if there are several separate domains of differently oriented second folding motions (i.e. several directions of a_2), then several distinct first hinge planes will result. These will cross at the original orientation of f_1. Figure 14 shows the first hinge planes for each individual first generation hinge actually observed in the

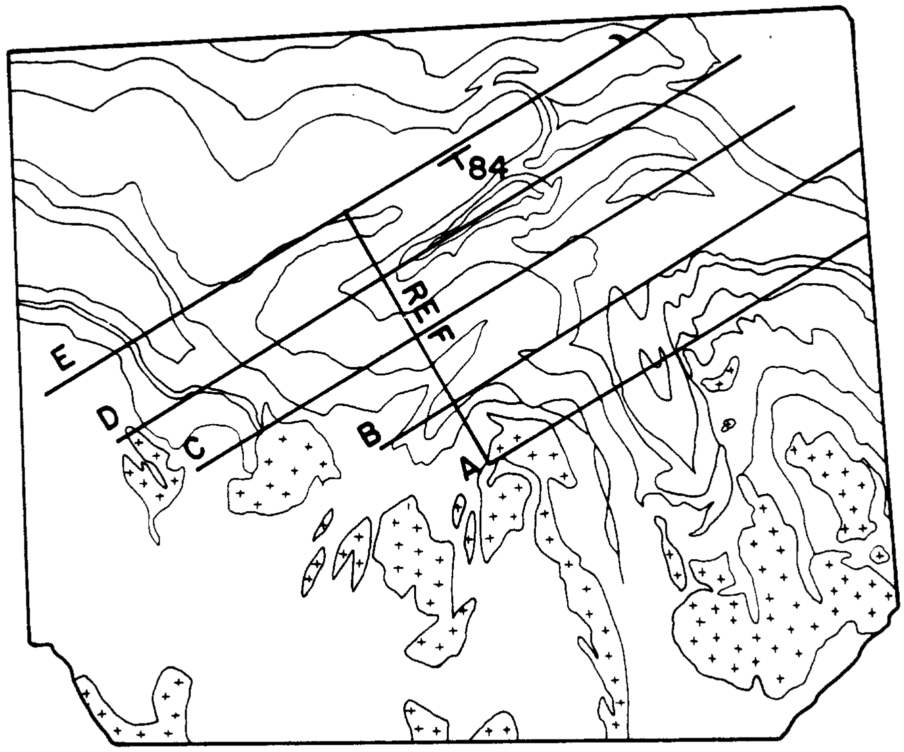

Fig. 9. Locations of five sections parallel to the first hinge plane. The sections dip 84° SE.

sample. As can be seen, an original orientation for f_1 is indicated at the intersection of these planes. Because a_2 is given by the intersection of the first and second hinge planes, a small range in orientation of a_2 is indicated. This is possibly due to non-passive behaviour of bedding or the presence of the quartz–feldspar boudins.

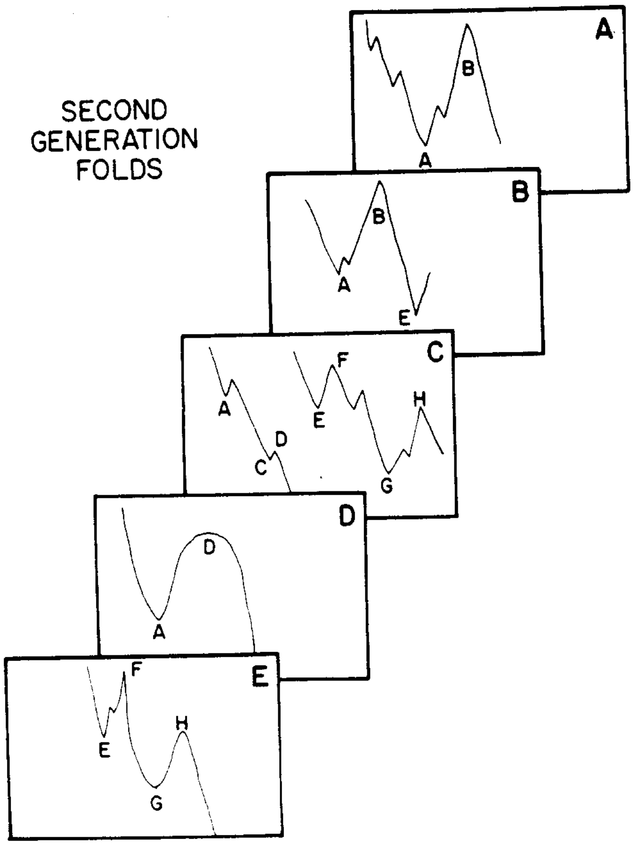

Fig. 10. Skewed views of the second fold waveforms as seen schematically in the sections located on Fig. 9. Individual second-generation folds are noted with letters.

One could take a different view of the entire problem and consider the second folding motions to occur in two components of simple shear parallel to c_2, one differential and containing all the waveforms, and the other constant over the entire area. Then one could talk in terms of the position of f_1 after the constant component but before the differential component. In our example, it would simply be represented by the average main cluster of the observed hinge directions (Fig. 4). This orientation is designated f_1' on Fig. 13; and is actually fairly close to f_1 as determined by Ramsay's intersection technique.

The first axial plane must pass through f_1. If one other ray within the axial plane could be determined, then the

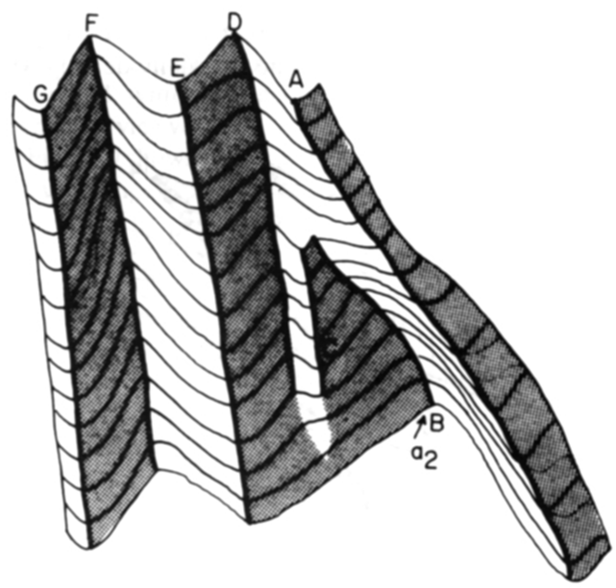

Fig. 11. Three-dimensional cartoon of the second generation folds based on sections of Fig. 10.

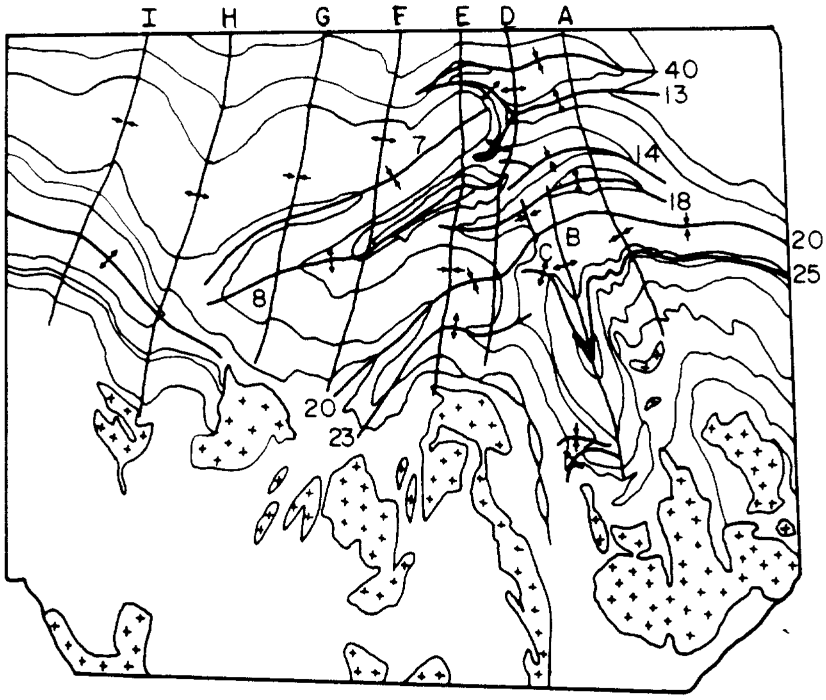

Fig. 12. Sketch of level 8 showing the interpretation of axial planes of the first- and second-generations. Synforms and antiforms are noted. The numbers and letters correspond to the first- and second-generation hinges shown in Figs. 7, 8, 10, and 11.

orientation of the plane and hence c_1 is defined. This second ray can be obtained from the sections cut parallel to the second hinge plane (Fig. 7). These sections show traces of the first fold axial planes. These traces define a ray, denoted i_{12}, which is the intersection of the section and the first axial plane. Its orientation can easily be obtained since it by definition lies within the second hinge plane, and its rake can be readily measured. Notice that the direction of the i_{12} ray is not affected by the second folding because the ray lies within the shear (axial) planes of the second folds. Therefore it gives a measure of the original orientation of the first axial plane. If f_1 and i_{12} are plotted on a stereonet (Fig. 13) the original orientation of the first axial plane is the plane containing these two points. c_1 will simply be the pole to the plane. Notice that the first axial plane and the first hinge plane are distinct in orientation but nearly parallel.

The orientation of the analyzed sample was unknown. However, the structural elements determined from it provide intriguing information for the Kootenay Arc. The main clusters of the first and second fold hinges (Figs. 4 and 5) are close together (f_1' and f_2 in Fig. 13), matching the nearly coaxial relationships observed in the field. The original orientation of f_1 is not however coaxial with f_1' and f_2, but the second slip direction (a_2) is within ten degrees of f_2. Apparently, there was a significant amount of rotation of the first fold hinges towards a_2, creating the nearly coaxial field relationships. Also, the observed second folds (f_2) were created by motions (a_2) almost parallel to themselves, and therefore almost parallel to the bedding planes being folded. The motions that created the folds had to be much larger than the folds themselves, and the tight second folds observed were probably caused by even tighter folding motions.

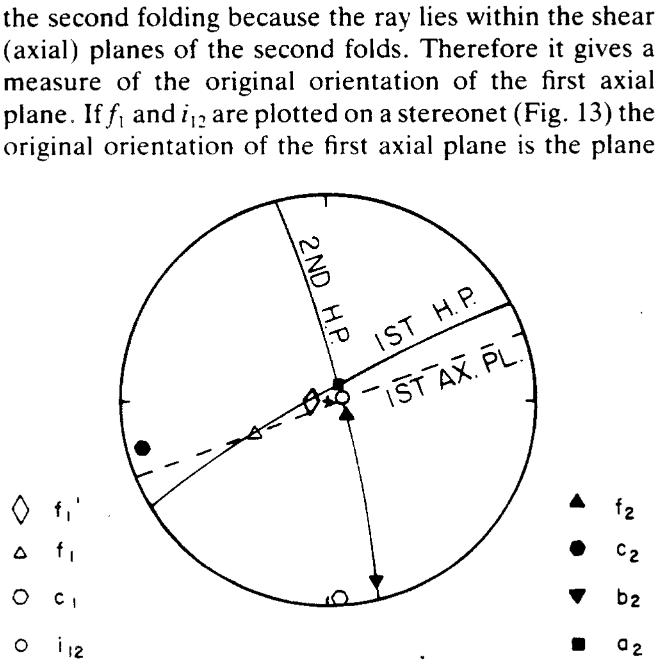

Fig. 13. Stereonet summary of structural data for the analyzed sample. The first hinge plane is labelled 1ST HP. The first axial plane is designated 1ST AX. PL. The second axial plane is also the second hinge plane, and is labelled 2ND HP. Notice that the first hinge plane and second axial plane cross at a_2. See text for details.

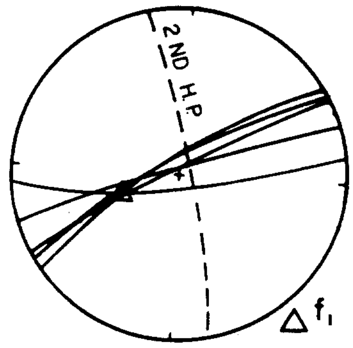

Fig. 14. Stereonet of first hinge planes defined by individual first generation hinges. The original orientation of f_1 will be given by their intersection (Ramsay 1967).

DISCUSSION AND CONCLUSIONS

The technique described herein is based upon several limiting assumptions. These are that the first folds are cylindrical and that the second folds can be described as having been formed by differential simple shear. These concepts are implicit in the 'mechanics' of Fig. 3. If layering does not behave passively during the folding events, problems might arise, as suggested, for example, by concentric folds or folds exhibiting cleavage refraction. Numerous workers (Ghosh & Ramberg 1968, Skjernaa 1975, Watkinson 1981) have shown that first fold hinges may add an element of anisotropy to the rock, strengthening it parallel to the hinges themselves. In a situation such as this, the second folds would not be similar folds. Figures 8 and 11 show that the analyzed sample is characterized by two generations of non-cylindrical and non-similar folds. Yet this technique not only worked, but it actually displayed the non-ideal nature of the folds. This is probably due in large part to the tight to isoclinal nature of the first folds, such that the second folds were basically affecting nearly parallel bedding planes.

A second problem would arise if a refold had been formed by more than two folding episodes. An attempt to use this technique should rapidly identify this problem. A third problem is simply identifying which generation each fold hinge belongs to, and figuring out continuity of a single hinge from one level to the next. Yet another problem is one of hinge migration. O'Driscoll (1962) demonstrated this effect with card deck models. Interaction of two nearly parallel folds often will produce an apparent fold hinge part way between the two. This effect is also evident when a fold hinge interacts with an oblique surface or surfaces.

The technique described above fills a major gap in the analysis of refolded folds. A previously published technique (Carey 1962, Ragan 1973) enabled the unravelling of coaxial (type 3) refolds. Our technique works on non-coaxial (types 1 and 2) refolds, and so the two techniques are complementary. Coaxial refolds are more often recognized in the field because they are easier to interpret. Non-coaxial or even nearly coaxial refolds are more of a challenge. They are harder to interpret and may not even be recognized as refolds. As this new technique is used in future applications, structural geologists should become more familiar with refold geometries and be able to interpret them more readily. Analysis of samples from classic refold areas, such as Loch Monar in Scotland (Ramsay 1958, Watkinson & Thiessen unpublished) would be useful. This technique is also ideal for refolded ore bodies, where mining levels give the necessary three-dimensional control, and its use may also lead to predictions of the shape of the ore body in undeveloped areas. Thiessen & Brown (1985) use computer simulations to lead to a fuller understanding of the refolded rocks in the Galena–Roubaix district in South Dakota. However, the quality of such predictions directly depend on how closely the folds match the assumptions of cylindricity and similarity, and whether the fold shapes continue as determined into the unknown areas.

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