Classification of Refold Structures

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ABSTRACT

Structural geology textbooks distinguish among four end members of three-dimensional refold structures established from their two-dimensional interference patterns. Here it is shown that six different end members of three-dimensional refold structures exist. These end members can be described by a reduced direction cosines matrix $\mathbf{L}^*$. The classical types 1–3 are extended to have three new counterparts types 0_1–0_3, which are derived by 90° rotation of the superposed fold around its fold axis. The matrix $\mathbf{L}^*$ can be used to characterize the angles between the two fold generations in a simple triangle plot illustrating the six end members and even any intermediate refold structure.

Introduction

Superposition of folding either during progressive displacement or different phases of deformation results in three-dimensional refold structures that are exposed on two-dimensional sections as interference patterns (Ramsay 1962). Kinematic models using either simple card decks (e.g., Carey 1962; O'Driscoll 1962) or computer programs (e.g., Thiessen and Means 1980; Perrin et al. 1988; Jessell and Valenta 1996; Ramsay and Lisle 2000; Vacas Peña 2000; Moore and Johnson 2001) have been successfully applied to simulate three-dimensional refolding and to study two-dimensional interference patterns on arbitrarily oriented sections through the modeled structures. On the basis of the results of these models, refold structures have been divided in structural geology textbooks into four types (types 0–3), depending on their characteristic two-dimensional interference patterns (Ramsay 1962, 1967). A major shortcoming of this classification is that it is derived from interference patterns, although kinematic modeling suggested that the shapes on two-dimensional intersections are not unequivocally diagnostic for the three-dimensional refold structure (e.g., Thiessen and Means 1980). Confusingly, most studies on fold superposition either field or model based use type 0–3 classification synonymously for two-dimensional interference patterns and three-dimensional refold structures. Inconsistently, descriptions such as "crescent," "mushroom," "hook," "bird's head," "dog's tooth," and "S-Z-W-M" shapes (Ramsay 1967; Thiessen 1986) fail to distinguish between either two- or three-dimensional forms.

Computer animations of fold superposition recently suggested that six end members with different kinematic evolutions should be distinguished (Fusseis and Grasemann 2002). Inspired by this work, we extend the existing classification by means of simple geometric considerations. Although we are aware that active layer buckling has a strong influence on the progressive development of refold structures (e.g., Grujic et al. 2002 and references cited therein) and that the refold structures of superposed buckling folds are strongly dependent on the fold shapes and interlimb angles (Ghosh et al. 1993), we use the same inherent limitations of kinematic models, which have led to the currently accepted terminology since the classical article of Ramsay (1962). Consequently, the aim of this study is twofold. First, it is demonstrated that mathematically not four but six end members of refold structures exist. Second, a new simple plot is introduced in order to quantify the spatial relationship between the initial and superposed fold orientations of all six end members including all intermediate structures.

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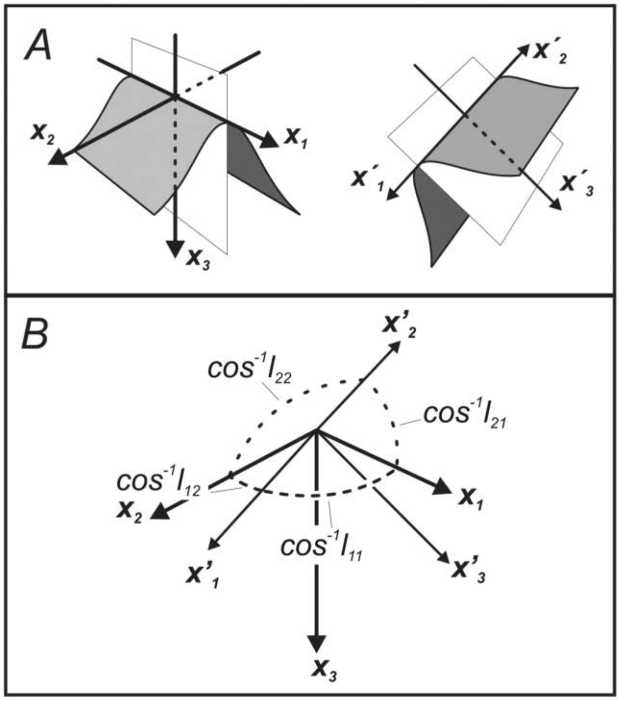

Figure 1. *A*, Reference axes are defined by the fold axis, normal to the axial plane and shear direction in the axial plane of the initial fold (x_1, x_2, x_3), and the superposed fold (x'_1, x'_2, x'_3). *B*, From the interaxial angles, the components l_{ij} of the reduced direction cosines matrix $\mathbf{L}^*$ are derived. Because of the orthogonality criteria, only four components are needed for the description of the spatial relation of both reference frames.

To avoid confusion, the term "refold structures" is used for three-dimensional shapes, including marker horizons on layers resulting from fold superposition. "Interference patterns" is used for the shapes on two-dimensional sections through refold structures.

Classification of Refold Structures

Traditionally, refold structures are distinguished by interaxial angles between reference axes of the initial and the superposed fold generation (Carey 1962; Ramsay 1967). The reference axes are the fold axis, the pole to the axial plane, and the shear direction in the axial plane (fig. 1). If orthorhombic shear folds are assumed, the reference axes are defined by a three-dimensional Cartesian coordinate system. Between the reference axes of the initial fold and those of the superposed fold, nine interaxial angles are possible, two of which were used to classify the four end members of fold interference patterns (Carey 1962; Ramsay 1967). Thiessen and Means (1980) used three angles to represent refold structures in a complex three-dimensional orientation volume, emphasizing that for a unique definition of the spatial orientation of initial and superposed reference axes, four interaxial angles are necessary.

Alternatively, the relative orientations of the initial and superposed reference axes can be considered as a rotation about the origin by an orthogonal direction cosine matrix $\mathbf{L}$:

$$\mathbf{L} = \begin{pmatrix} l_{11} & l_{12} & l_{13} \\ l_{21} & l_{22} & l_{23} \\ l_{31} & l_{32} & l_{33} \end{pmatrix}, \tag{1}$$

where

$$\cos^{-1} l_{11} = \angle x'_1 x_1;\ \cos^{-1} l_{12} = \angle x'_1 x_2;\ \cos^{-1} l_{13} = \angle x'_1 x_3;$$

$$\cos^{-1} l_{21} = \angle x'_2 x_1;\ \cos^{-1} l_{22} = \angle x'_2 x_2;\ \cos^{-1} l_{23} = \angle x'_2 x_3;$$

$$\cos^{-1} l_{31} = \angle x'_3 x_1;\ \cos^{-1} l_{32} = \angle x'_3 x_2;\ \cos^{-1} l_{33} = \angle x'_3 x_3.$$

Because of the assumed orthorhombic symmetry of the folds, l_{ij} is allowed to take values between 0 and 1. By definition the direction cosine requires that (no sum on i)

$$\mathbf{L}_{ij}\mathbf{L}_{ij} = \mathbf{L}_{ji}\mathbf{L}_{ji} = 1, \tag{2}$$

and therefore, $\mathbf{L}$ can be replaced by a reduced two-dimensional direction cosine matrix $\mathbf{L}^*$:

$$\mathbf{L}^* = \begin{pmatrix} l_{11} & l_{12} \\ l_{21} & l_{22} \end{pmatrix}, \tag{3}$$

where, because the angles are measured from one line to two orthogonal lines (no sum on i),

$$0 \le \mathbf{L}_{ij}\mathbf{L}_{ij} = \mathbf{L}_{ji}\mathbf{L}_{ji} \le 1. \tag{4}$$

Furthermore, because the orthogonality relation must hold (Nye 1960),

$$l_{11} + l_{12} + l_{21} + l_{22} \ge 1. \tag{5}$$

Orthogonal end members of refold structures, where the reference axes of the initial and superposed fold are either perpendicular or parallel to each others, are characterized by $\mathbf{L}^*$, of which the elements are either 0 or 1. Neither a row nor a column is allowed to consist of elements both of which are equal to 1 (eq. [4]). Additionally, all elements are not allowed to be 0 (eq. [5]), and consequently six orthogonal end members mathematically exist.

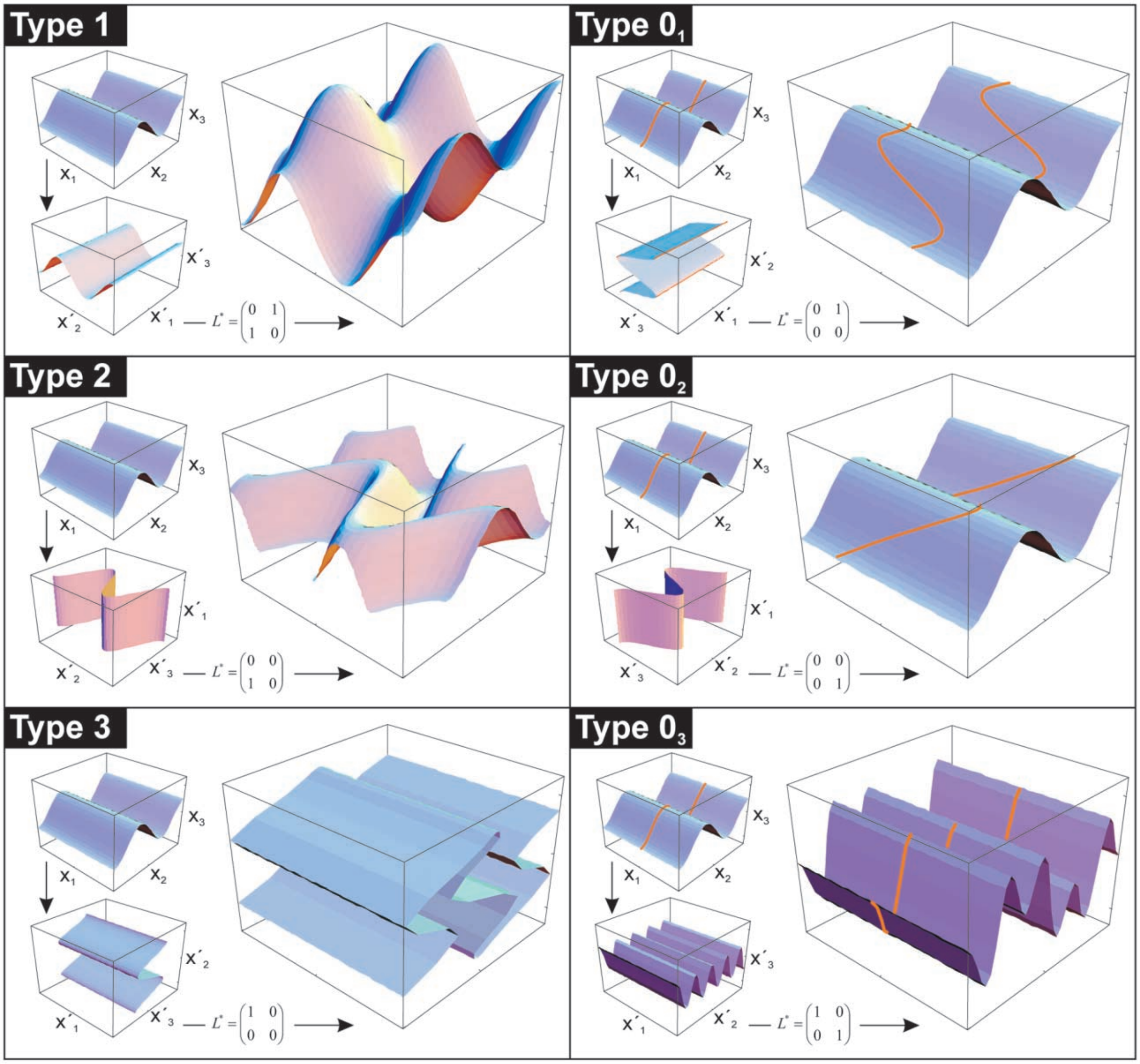

Figure 2. Three-dimensional geometry of the six end-member refold structures. Marker lines on type 0_1–0_3 refolds clearly reveal the different finite deformation recorded by the structures. In order to highlight the geometry of type 0_3 refolds, the superposed fold has a three times shorter wavelength responsible for the second-order folds of the finite structure. The kinematic models were calculated using the software Mathematica (Wolfram 1999) and the package FoldPlot (Moore and Johnson 2001).

Following the suggestions of Fusseis and Grasemann (2002), the presented terminology extends the well-established existing classification in the following points. The terminology is used for end members of three-dimensional refold geometries and not for two-dimensional interference patterns; type 0 refolds are subdivided into three geometrically individual end members types 0_1–0_3. Although not independent, four angles (expressed by the components of $\mathbf{L}^*$) instead of two (e.g., Ramsay 1967) or three (e.g., Thiessen and Means 1980) are needed to characterize the full range of refold structures.

Six end members of refold structures are distinguished, two of which are newly defined (fig. 2): Type 1: Identical to the existing type 1 refold structure frequently leading to dome-basin interference patterns. Type 2: Identical to the existing type 2 refold structure frequently leading to dome-crescent-mushroom interference patterns. Type 3:

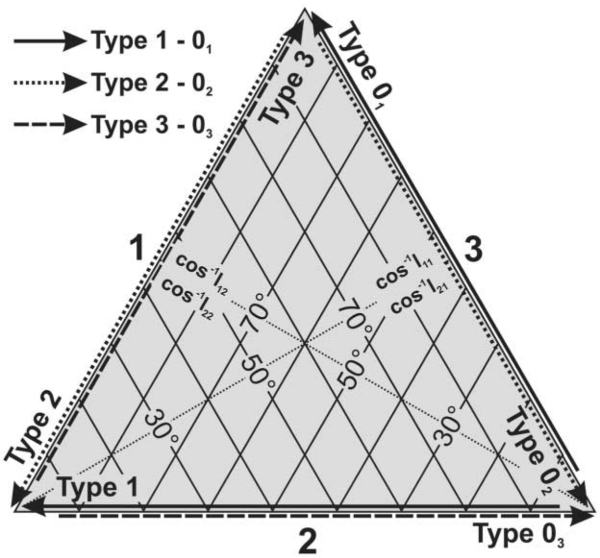

Figure 3. Vector triangle plot for the graphical quantification of the interaxial angles of refold structures. Each side represents two of the possible six end members as vectors with opposite polarity. For the construction technique, see text.

Identical to the existing type 3 refold structure frequently leading to convergent-divergent interference patterns. Type 0_1: Newly defined refold structure, although the geometric possibility has already been mentioned by Thiessen and Means (1980). The shearing direction of the superposed fold is the direction of the initial fold axis. The shear planes are perpendicular to the axial plane of the initial fold. Neither the axial planes nor the folds axes of the initial and the superposed folds appear deformed, and the resulting refold structure is identical to the shape of the initial fold. However, a passive marker on the layer surface of the initial fold perpendicular to the fold axis, which is deformed by the second fold generation, clearly demonstrates the superposition of heterogeneous deformation. Type 0_2: Newly defined refold structure. The shearing direction and the shear plane of the superposing fold are parallel to the initial fold axis and axial plane respectively. The resulting refold structure is identical to the shape of the initial fold. A linear passive marker on the initial fold surface normal to fold axis reveals the superposition of heterogeneous deformation. However, the deformation of the linear marker is clearly different from the finite deformation of type 0_1. Type 0_3: Renamed refold structure, which is identical to the traditional type 0 redundant superposition.

The Vector Triangle Plot

Currently, no plot exists for unequivocally quantifying the spatial relationship between the initial and the superposed fold of refold structures. Here, we suggest a simple vector diagram, which has the advantage that four interaxial angles of $\mathbf{L}^*$ uniquely define the full range of possible refold structures including the six end members (fig. 3). The construction is as follows. Select a contour line parallel to the right side of the triangle, which represents the angle between the superposed and the initial fold axis ($\cos^{-1} l_{11}$). Intersect this line with a second contour line parallel to the left side of the triangle, which represents the angle between the superposed fold axis and the normal of the axial plane of the initial fold ($\cos^{-1} l_{12}$). This intersection is the origin of a vector. Repeat the construction for the angle between the normal to the axial plane of the superposed fold and the fold axis of the initial fold ($\cos^{-1} l_{21}$) as well as the normal of the axial plane of the initial fold ($\cos^{-1} l_{22}$). This intersection is the point of a vector characterizing together with the origin the refold structure. All six end-member refold structures plot as vectors with different polarities along the three sides of the triangle plot. Types 1–3 together with their types 0_1–0_3 counterparts always point from one edge along two sides toward the opposite side (fig. 3).

Transition between End-Member Refold Structures

According to the binomial coefficient, 15 transitions between two out of six possible end members theoretically exist, which can be grouped into the four classes below.

Rotation of the superposed fold around its fold axis x_1' (fig. 4*A*) generates three intermediate members: type $1 \leftrightarrow 0_1$, type $2 \leftrightarrow 0_2$, and type $3 \leftrightarrow 0_3$. A full transition of one end member into the other needs a rotation around x_1' by 90°. In the triangle plot, these structures have vectors starting at the same corner as the end-member structures and pointing toward the opposite side. Intermediate members, exactly between the end members (rotation around x_1' by 45°), plot as the heights of the triangle pointing from a corner toward the opposite side.

Rotation of the superposed fold around the normal to its axial plane x_2' (fig. 4*B*) generates three intermediate members: type $1 \leftrightarrow 2$, type $0_2 \leftrightarrow 0_3$, and type $3 \leftrightarrow 0_1$. A full transition of one end member into the other needs a rotation around x_2' by 90°. In the triangle plot, these structures have vectors

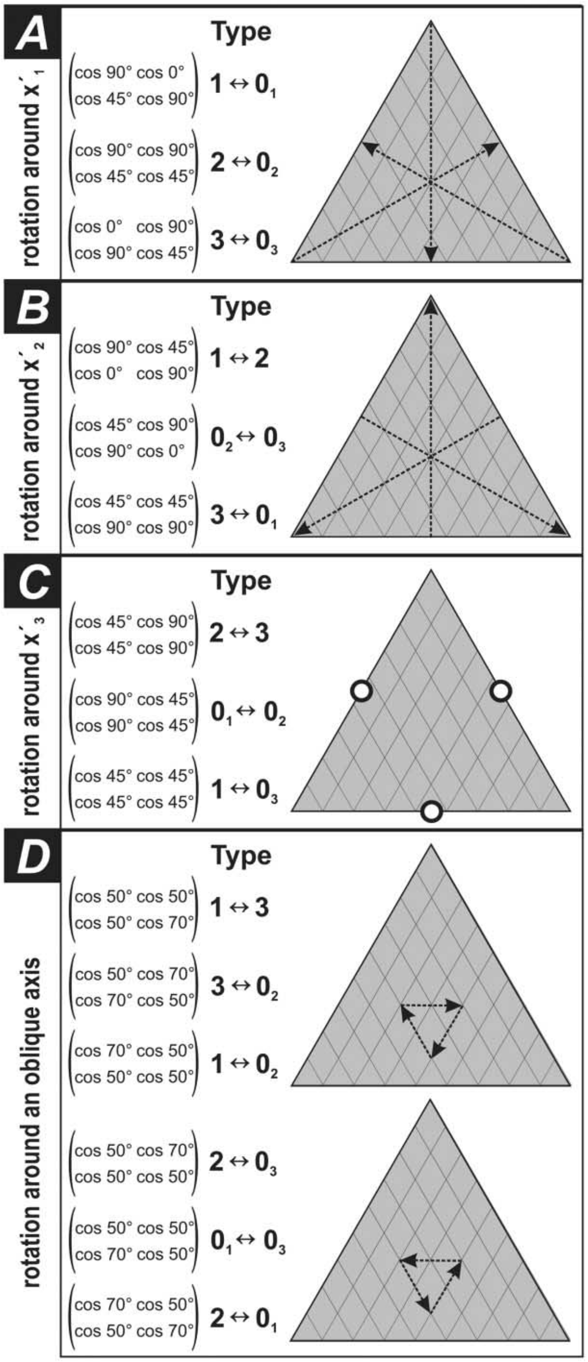

Figure 4. Vector triangle plots and reduced direction cosines matrix $\mathbf{L}^*$ for the 15 possible intermediate types between the six end-member refold types. *A*, Rotation of the superposing fold by 45° around its fold axis (x_1'). *B*, Rotation of the superposing fold by 45° around the normal to its axial plane (x_2'). *C*, Rotation of the superposing fold by 45° around the shear direction in its axial plane (x_3'). *D*, The remaining six intermediate refold members represent rotations between end members by 60° around an oblique axis with direction cosines ($\sqrt{3}^{-1}$, $\sqrt{3}^{-1}$, $\sqrt{3}^{-1}$).

pointing into the same corner as the end-member structures and starting at the opposite side. Intermediate members, exactly between the end members (rotation around x_2' by 45°), plot as the heights of the triangle pointing from a side toward the opposite corner.

Rotation of the superposed fold around its shear direction x_3' (fig. 4*C*) generates three intermediate members: type $2 \leftrightarrow 3$, type $0_2 \leftrightarrow 0_3$, and type $3 \leftrightarrow 0_1$. A full transition of one end member into the other requires a rotation around x_3' by 90°. In the triangle plot, these structures have vectors plotting along the same side as the end-member structures. Incremental transition of one end member into the other plot as vectors with decreasing length, which switch the polarity exactly at a point in the middle of the triangle side (rotation around 45°) increasing again in length.

Rotation of the superposed fold around an oblique rotation axis (fig. 4*D*) has six continuous series between the end members. These intermediate members develop during rotation around an oblique rotation axis given by the direction cosines of $\sqrt{3}^{-1}$, $\sqrt{3}^{-1}$, $\sqrt{3}^{-1}$ by 120°. These structures comprise type $1 \leftrightarrow 3$, type $2 \leftrightarrow 0_3$, type $3 \leftrightarrow 0_2$, type $2 \leftrightarrow 0_1$, type $1 \leftrightarrow 0_2$, and type $1 \leftrightarrow 3$. Intermediate members exactly between the end members (rotation around 60°) plot as vectors within the triangle pointing from one to the other end-member side of the triangle parallel to the third side.

Discussion

Geological Relevance of Type 0_1–0_3 Refolds. The following discussion emphasizes the geological significance of a geometric discrimination between type 0_1–0_3 refold structures, leaving the question of their mechanical likeliness open for further investigations.

Type 0_1 has been mentioned already by Thiessen and Means (1980) but has been considered as mechanically unlikely. However, the superposition of recumbent shear folds on upright folds with fold axes parallel to the shear direction probably forming type 0_1 refold structures may most likely have a close kinematic relationship in large detachment zones (Mancktelow and Pavlis 1994).

A superb example of a natural type 0_2 refold from the Singhbhum shear zone (India), including a physical model of an intermediate type $2 \leftrightarrow 0_2$ structure, has been published recently by Sengupta and Koyi (2001). The experiments produced by Grujic and Mancktelow (1995) are comparable to the kinematic axes of type 0_2 refolds. Furthermore, it is generally accepted that, in shear zones, passive, highly noncylindrical folds may develop by amplifications of deflections eventually forming sheath folds (e.g., Cobbold and Quinquis 1980). Progressive shear deformation of such sheath folds could develop type 0_2 along both limbs and type 0_3 refold structures at the nose. Considering incremental superposition of deformation, type 0_3 structures are probably the most common refold structures in nature, which permanently form during amplification of folds (Thiessen and Means 1980). Considering that individual fold sets are uniform neither in scale nor orientation and that variable strain may result in both fold hinges and axial planes undergoing significant rotations, type 0_1–0_3 refold structures are likely to form during progressive development of flow perturbation folds (Alsop and Holdsworth 2002).

A detailed investigation of possible scenarios for the formation of type 0_1–0_3 refold structures is out of scope of this work. However, the spatial geometric relationship between initial and superposed fold for the formation of type 0_1–0_3 structures can be expected in many natural settings such as folded convolute soft sediment deformation (Ghosh et al. 2002), within the bulbs of mushroom-shaped diapirs (Jackson and Talbot 1989), or multiply deformed sheath folds (Fowler and El Kalioubi 2002). Although the fold shapes of type 0_1–0_3 end members do not show interference patterns indicative of fold superposition, a slight deviation of the end-member geometry may result in markedly different refold shape as can be clearly observed in the computer animations of Fusseis and Grasemann (2002). Marker lines on the folded layers (e.g., a preexisting stretching lineation) or the introduction of marker planes before fold superposition (e.g., extension fissures, the intrusion of a dyke) would clearly highlight the marked difference in finite heterogeneous deformation among type 0_1–0_3 structures.

Lüneburg and Lebit (1998) investigated Variscan refold structures in SW Sardinia, demonstrating that a single penetrative cleavage formed, which is not unambiguously correlated with either of the folding events. Finite strain determination suggests that the cleavage always parallels the principal plane of finite strain. Because the finite strain and thus the cleavage are markedly different in type 0_1, 0_2, and 0_3 refold structures, we suggest that careful investigations of finite strain could reveal natural examples. Modeling of three-dimensional heterogeneous displacements in order to investigate finite strain in refold structures has been suggested by Ramsay and Lisle (2000), challenging the comparison of strain patterns in theoretically modeled and natural examples of type 0_1, 0_2, and 0_3 refold structures.

Application of the Vector Triangle Plot. The presented vector triangle plot requires the knowledge of the orientation of the initial and superposed fold, which limits its practical use for plotting spatial field data. Nevertheless, several attempts have been made to quantify the angular relationship of the reference axes of the different fold generations in graphical plots (Ramsay 1967; Thiessen and Means 1980), and their common use in structural geology textbooks justifies the efforts to make such diagrams as simple and comprehensive as possible. Unfortunately, all existing plots either are too simple by quantifying just two or three of the four necessary interaxial angles or have complex three-dimensional shapes. The strength of the presented vector triangle plot is that it is a simple triangular diagram, where each side represents two of the possible six end members as vectors with opposite polarity. By choosing two different end members, the vector representation of the intermediate refold type can be easily envisaged by gradually transforming the vector of the one end member into the vector of the other end member. This makes the diagram most useful for analyzing natural structures or the results of physical and numerical forward models where the kinematic boundary conditions are known, but the resulting structures represent a broad range of intermediate refold members.

Limitations. The suggested classification is based on kinematic modeling assuming simple shear folding and consequently does not consider strong layer competence contrast that might influence the fold geometry in a way that would lead to progressive amplification and deamplification of the layer stack. This simplification might be criticized as being oversimplified and of somewhat limited geological application because recent physical models have confirmed the enormous influence of the mechanical properties (e.g., Grujic et al. 2002 and references cited therein). However, the currently well-established classification of refold structures, or, strictly speaking, interference patterns, is based on the same kinematic assumptions that were used in this study. Consequently, the new suggested classification is an extension of the existing incomplete terminology.

Conclusions

1. It is recommended to use "refold structures" consistently for three-dimensional shapes of deformed layers resulting from fold superposition, in-

cluding marker horizons on layers. "Interference patterns" should be exclusively used for the shapes on two-dimensional sections through refold structures, which are not unequivocally diagnostic for classification.

2. Based on a reduced direction cosines matrix $\mathbf{L}^*$, six end members of refold structures must exist.

3. The well-established terminology of fold superposition classifying types 1–3 is extended to have three counterparts types 0_1–0_3, which are simply derived by 90° rotation of the superposed fold around its fold axis.

4. Although the type 0_1–0_3 refold structures do not cause a visible folding of the initial fold axis and/or axial plane, their heterogeneous incremental strain pattern is markedly different, justifying their discrimination as different end members. Any deviation of the ideal end-member geometry or any marker lines or planes at high angle to the initial fold axis results in obvious different structures.

5. The matrix $\mathbf{L}^*$ can be furthermore used to characterize the spatial relationship between two fold generations in a simple triangle plot.

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