真三維三角剪切模式：適用於走滑斷層與斜滑斷層變形的運動學模型

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摘要

三角剪切模式（Trishear Model）已發展數十年，主要運用於分析斷層、褶皺或地層變形的幾何形狀、應變分布或預估破裂的位置，但是經典軟體如FaultFold 的分析限於二維、或假三維的運算，僅適用於傾向滑移斷層（Dip-slip fault），而走向滑移或斜滑斷層的分析一直到本文發表、提供真三維的運算解算後才得以確立。本研究最重要的貢獻即是發展出一套三維視覺化的三角剪切軟體，在地理座標與斷層面座標系統之間可自由轉換，其基本假設為流體不可壓縮性、三角剪切變形帶內的運動速度場為體積守恆。

本研究數值模型可分析廣大的範圍並獲得詳細的變形特徵，經由分別調整平行於斷層走向的滑移量與頂角角度（apical or trishear angle），模擬結果顯示伸張裂縫（tension cracks）與剪切裂縫（Shear cracks）與走向滑移斷層常見的裂隙構造方向相符，例如馬尾狀構造、雷利剪切（Riedel shear）構造、甚至是開花狀構造的雛形。此外，上述模擬的破裂面在平行於或垂直於斷層走向時，其移動的行為與主應變軸的變化相符。最後比對數個走滑斷層的自然實證以及沙箱模型實證，例如壓縮型的正開花構造、張裂型的負開花構造、斷層反轉模式，均與本研究數值模型大致相符。然而，此模式並不完美，例如進行斷層反轉（Inversion）方法太耗時、分析傾向滑移斷層時與偽三維模型相比較不方便。

關鍵字： 三角剪切模式、走向滑移斷層、斜滑斷層、數值模型、裂隙、斷層擴展褶皺

True three-dimensional trishear: A kinematic model for strike-slip and oblique-slip deformation

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ABSTRACT

Most structural/kinematic models are inherently two-dimensional; even several recent three-dimensional models are "pseudo–three-dimensional" in that they consist of a series of parallel two-dimensional cross sections. Lack of a true three-dimensional formulation hampers our abilities to simulate three-dimensional structures such as oblique- and strike-slip faulting and displacement gradients perpendicular to the slip vector. The mathematical formulation of trishear deformation using incompressibility of flow is well suited to a solution in three dimensions. We derive one plausible velocity field for true three-dimensional flow in a triangular shear zone. This formulation allows us to simulate the deformation in oblique-slip deformation zones as well as flower structures associated with strike-slip fault zones. The strain distribution in flower structures combined with some simple mechanical assumptions suggests that faults in these zones would have a helicoidal geometry. The results of the kinematic model compare well to well-described structures in the Colorado Plateau, Andaman Sea, and Death Valley, as well as to data from analogue experiments.

Keywords: trishear, strike-slip, numerical model, fault-propagation deformation, oblique-slip, fractures.

INTRODUCTION

A number of mineral deposits and hydrocarbon reservoirs are related to flower structures along strike-slip deformation zones (e.g., Dorsal Neuquina fault system: Vergani et al., 1995; Andaman Sea fault: Harding, 1985; Athos fault: Roussos and Triantafyllos, 1991); in addition, significant earthquake activity along others threatens major population centers (e.g., San Andreas–Garlock system, North Anatolian fault, etc.). Numerous authors have studied this style of deformation, creating a systematic, descriptive classification (Woodcock and Fischer, 1986; Sylvester, 1988; Woodcock and Schubert, 1994). Many field examples (Harding, 1985; Dooley and McClay, 1996; Tindall and Davis, 1999) are well documented, and some analogue and mechanical models have also been presented (Richard and Krantz, 1991; Dooley and McClay, 1996; Dooley and McClay, 1997). However, despite the importance of strike-slip and oblique-slip fault zones, kinematic models to analyze them are virtually unknown because of the inherently three-dimensional nature of the deformation.

During strike-slip analogue experiments the first-formed structures are en echelon Riedel shears. Naylor et al. (1986) have shown that these structures are concave upward and have a helicoidal geometry such that they twist to merge with the principal displacement zone (PDZ) at depth (Naylor et al., 1986; Sylvester, 1988; Woodcock and Schubert, 1994) to form tulip or flower structures. However, it is not theoretically clear why this helicoidal geometry is formed. Naylor et al. (1986) explained it as a consequence of the en echelon pattern of the shears at the surface, their concave-upward geometry, and the need to join a single basement fault at depth.

The three-dimensional arrangement of these structures suggests the possibility that they have been formed in a triangular deformation zone where the apical line is the upper termination of the main fault (Fig. 1B). Here we present a novel application of the trishear kinematic model—initially proposed by Erslev (1991), later extended by Hardy and Ford (1997) and Zehnder and Allmendinger (2000)—that can be used to simulate the structure of strike-slip and oblique-slip deformation. Because Erslev's (1991) method is inherently two-dimensional, we first derive a three-dimensional solution based on incompressibility of flow. A computer program was written to apply this solution, and the results were compared with natural examples and analogue models.

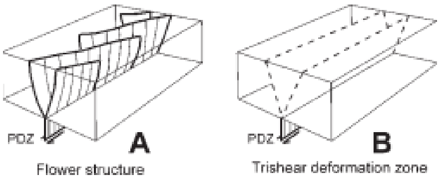

Figure 1. (A) Helicoidal geometry of Riedel faults (Naylor et al., 1986). PDZ—principal displacement zone. (B) Concept of trishear applied to strike-slip deformation.

The kinematic model that we present here is a true three-dimensional generalization of the trishear-model velocity field presented by Zehnder and Allmendinger (2000) and differs from Cristallini and Allmendinger's (2001) pseudo–three-dimensional approximation. Although the new model is in some ways less versatile than the pseudo–three-dimensional approach, it is much more powerful for successfully simulating oblique and strike-slip deformation.

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