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Finite strain analysis in the Seydan anticline using ammonoid spiral shells, Zagros, Iran

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ABSTRACT

Fossils with a spiral shape can be used as strain markers in quantitative strain analysis. Several methods have been suggested for strain analyses that exploit the logarithmic spiral laws governing development and growth of ammonoids. In this study, ammonoid spiral shells were measured to estimate strain variations along the northwestern limb of the Seydan anticline in the Zagros Fold-and-Thrust Belt, Iran. Results show an increase in strain from SE to NW along the Seydan anticline. These results, combined with other structural evidence, reveal a logical relationship between the intensity of folding and increasing strain. Strain variations are related to different amounts of slip along the Sivand thrust fault, which played a significant role in the development of the Seydan anticline as a fault-propagation fold.

1. Introduction

Most invertebrate animals (ammonites, goniatites, gastrapods) have shells with a spiral form. This spiral form is very similar to that known mathematically as a logarithmic spiral, first noted by Mosely (1838). Among the invertebrates with shells in a spiral form, planispiral ammonoids are the best know examples. Heim (1878, 1921) introduced a method for obtaining the amount of rock deformation using deformed ammonites. The first technique for strain measurement of logarithmic spirals was suggested by Blake (1878). Since then, a diversity of methodologies has been proposed to estimate finite strain, such as the R_f/Φ (Ramsay, 1967; Dunnet, 1969) and Fry methods (Fry, 1979). All methods that apply object or point displacement try to estimate the amount of tectonic strain and changes in shape and orientation of the strain ellipse/ellipsoid in 2D and 3D, respectively. In this study, we use ammonoid spiral shells as strain markers to quantify strain variations in the Seydan anticline of the Zagros Fold-and-Thrust Belt, Iran. Previous works include several strain analyses based on the application of the quartz *c*-axis method and measurements of deformed conglomerate pebbles in the Sanandaj–Sirjan metamorphic belt (Sarkarinejad, 2007; Sarkarinejad et al., 2008, 2010). However, strain measurements in the unmetamorphosed sedimentary rocks of the Zagros Fold-and-Thrust Belt have not been undertaken, particularly the limestones in the present-day foreland of the orogen. Our results of finite strain measurements of ammonoid shells show a close relationship with variation in fold style of the Seydan anticline and amounts of strain.

2. Tectonic setting of the Zagros Fold-and-Thrust Belt

The Zagros Fold-and-Thrust Belt is part of the Alpine–Himalayan orogenic belt (Takin, 1972; Berberian and King, 1981) and forms the northeastern margin of the Arabian Plate. The Zagros Fold-Thrust Belt contains an 8–14 km thick Cambrian-Recent sedimentary succession that rests on Precambrian metamorphic basement. These sedimentary rocks were deposited on a platform that was relatively stable from the Cambrian until the collision between the Arabian and Iranian plates in the Late-Cretaceous to Tertiary (Takin, 1972; Falcon, 1974; Berberian and King, 1981). Shortening across the Zagros Fold-and-Thrust Belt is estimated to be about 30–85 km (Falcon, 1974; Blanc et al., 2003; McQuarrie, 2004), and thought to have occurred by thrusting and folding above a number of décollement horizons (McQuarrie, 2004). Post-collisional crustal shortening is still active (Jackson and McKenzie, 1984; Talebian and Jackson, 2002; Allen et al., 2004; Tatar et al., 2004) due to N–S oriented convergence at approximately 20 ± 2 mm/yr^{-1} (Vernant et al., 2004; Molinaro et al., 2005). Shortening in the basement occurs dominantly by faulting. The thick Cambrian Hormuz Salt, at the base of the sedimentary succession, and other evaporite horizons (e.g. the Dashtak and Gachsaran Formations) within the

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succession (Berberian, 1981; Sepehr and Cosgrove, 2005; Talebian and Jackson, 2002), prevented these basement faults from reaching the surface. As a result of these decoupling horizons, the deformation in the basement and the sedimentary cover occurred independently (Sepehr and Cosgrove, 2005). The Zagros Fold-and-Thrust belt mainly consists of asymmetrical folds, which form a 200–300 km wide series of ranges extending for about 1800 km along strike from eastern Turkey to southeastern Iran, in the Strait of Hormuz. Here, the belt terminates against the Minab Fault (Fig. 1), which separates the Zagros Fold-and-Thrust Belt from the Makran accretionary prism (Molinaro et al., 2005). To the SW of the suture and within the Zagros Belt, a series of simple and recumbent folds have been developed with axial trends either parallel, or oblique, to the Zagros Thrust System. The present study area is located in the Seydan anticline near Sivand city, 100 km northwestern of Shiraz. The double-plunging Seydan anticline, like many anticlines in the Zagros Fold-Thrust Belt, has a fold axis with a NW–SE orientation. Based on the Iranian Geological Survey report of Yousefi and Kargar (2003), this anticline shows an asymmetrical geometry. The northeastern flank of the anticline has dips of up to 60°–90° with an overturned layer that is associated with the Sivand thrust fault. But the southwestern flank mainly shows bedding with average dips of 30°–50° SW. Therefore, it seems that the structural evolution and uplift of the Seydan anticline is a fault-related fold. Kinematic models of folding in the Zagros Fold-and-Thrust Belt mainly consist of a combination of flexural-slip and neutral-surface folding mechanisms, as indicated by detachment faults and bedding-plane slickenside lineations (McQuillan, 1974). The main part of the Seydan anticline consists of the Cretaceous Sarvak ?tul?> Formation, which is predominantly composed of carbonate rocks and represents one of the main hydrocarbon reservoir rocks in southwest Iran. In the study area, the Sarvak Formation mainly consists of light to grey calcareous breccia and medium-bedded limestone. The Sarvak Formation limestones in this area contain numerous spiral ammonite fossils. Fig. 2 shows the satellite image (ETM, Landsat 7) and the geological map of the study area.

3. Spiral shells as strain markers

Strain analysis involves converting information on length changes and angular distortions provided by strain markers to a more readily understood representation of the states of strain (Lisle, 1985). The measurement of strain in deformed rock uses, for its basis, the shape of markers of which some predeformational geometric features are known. The key to strain determination lies in objects that have a known, characteristic initial shape, initial packing arrangement, and/or some other features that enable post-deformational length or angle changes to be computed. Some of the most important strain markers have been described by Ramsay and Huber (1983). One example is fossils with a spiral shape, which were used as strain markers more than one hundred years ago (Blake, 1878). Ammonoid spiral shells are common fossils that are favored by structural geologist for the study of finite strain. Ammonoids are often strained homogeneously with the rocks because of low competency contrast between the shells and their host rocks, and because of the similarity of material filling the shells and forming the surrounding rocks. Shells with an internal filling of sediment or crystals of different composition or grain size from the surrounding host rock cannot be used as proper markers in strain analysis because the competence contrast between the shells and its surrounding matrix may differ and therefore not record the true total strain. Many spiral fossils are deposited on sub-horizontal bedding surfaces, and therefore lie with their shortest dimension perpendicular to the bedding plane. Therefore, the results of strain analysis using ammonoids mainly show the amount of strain on bedding planes, which is approximately parallel to the XY plane of the strain ellipsoid.

4. Ammonoid strain analysis methods

The recognition of a logarithmic growth of ammonoid shells opened the way for the establishment of several methods to calculate the amount of strain from deformed specimens. The form of

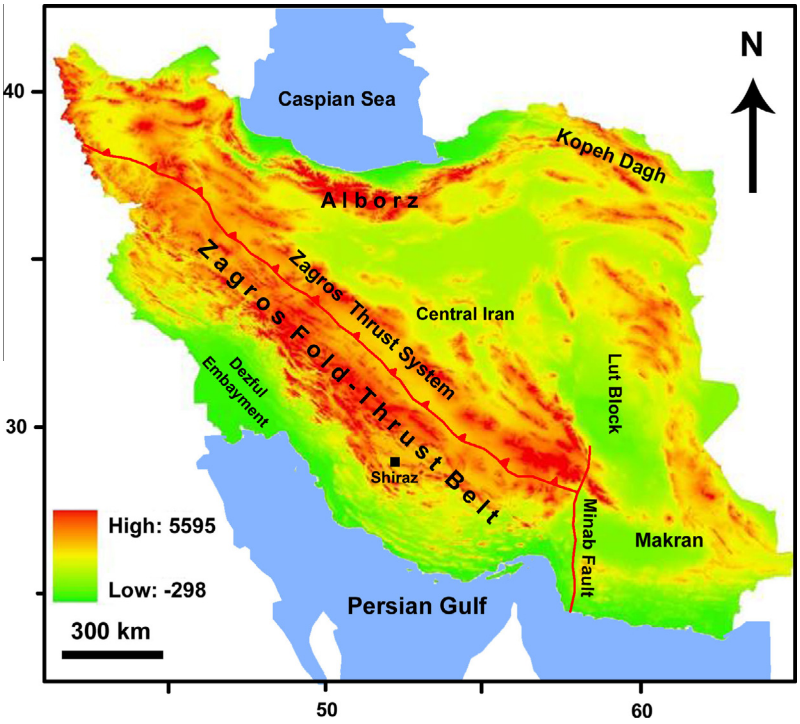

Fig. 1. Topographic relief and structural map of Iran. Zagros Fold-and-Thrust Belt bounded by the Zagros Thrust System in the north and Beshagard fault in the southeast.