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, gastropods) 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 known 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 Rf/Ø (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...
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
such a spiral can be expressed most generally in a parametric equation (Mosely, 1838; Tompson, 1942):

$$r = ke^{\frac{h}{\cot a}}$$

(1)

where $r$ is the radius of the spiral, $k$ is a constant of scale parameter, $\theta$ is the angle through which the curve has evolved, and $a$ is the spiral angle between the tangent to the spiral and the radius vector (Fig. 3a). The value of the spiral angle is related to the tightness of the spiral coil. Values close to $90^\circ$ give tightly coiled spirals, whereas lower angles show more open spirals (Fig. 4). From Eq., it can be found that the spiral angle ($\alpha$) controls the various shapes of spiral fossils. According to Tan (1973) the spiral angle for the Jurassic ammonoids always varies between 80$^\circ$ and 84$^\circ$. In order to estimate the strain from deformed ammonoids, two different methods have been proposed by Blake (1878) and Tan (1973), using linear and angular parameters, respectively. The first method is based on determining the amount of strain of the spiral fossils from computing the strain ratio after measuring the dimensions of the polar radius of the deformed spiral parallel to the directions of the principal strains. In Fig. 3b if the direction of maximum elongation is coincide with the $AC$, Blake (1878) shows that the finite strain axial ratio is given by:

$$\left(\frac{\alpha_1}{\alpha_2}\right)^{1/2} = \frac{\text{AO-OC}}{\text{OD}}$$

(2)

Tan’s method uses a fundamental property of the logarithmic spiral, that the tangent at any point of a logarithmic spiral makes a constant angle with the polar radius vector. This constant spiral angle is utilized in the Tan (1973) technique of strain analysis. After deformation, the spiral angle ($\alpha$) changes to ($\alpha'$) (Fig. 3b) and varies with position of the tangent with respect to the princi-
pal strain axes. It is possible to measure the angles, $\theta \pm (90^\circ - \alpha)$, (angle between radius vector and direction of maximum length of spiral and $\psi \pm (90^\circ - \alpha)'$, (angle makes by radius vector with the normal to the tangent at any point on the spiral) from a deformed spiral fossil (Fig. 3b). The angles $\theta \pm (90^\circ - \alpha)$ and $\psi \pm (90^\circ - \alpha)'$ are related to the $(k_1/k_2)^{1/2}$ and the initial spiral angle $(\alpha)$. The variation of these angles can be calculated for wide range of $(k_1/k_2)^{1/2}$ values and different values of the spiral angle. In this approach, the strain of the ammonoid can be found if values of these angles are known. The graphical functions for $\alpha = 80^\circ, 82^\circ$ and $84^\circ$ have been presented by Tan (1973). Plotting $\theta \pm (90^\circ - \alpha)$ and $\psi \pm (90^\circ - \alpha)'$ data on these graphs show that points fall approximately on, or about, one of the curves of the graphical function. In real situations, the fossil data always show some scattering in relation to the theoretical curves. This scattering occurs rather due to the failure of the ammonoid shell to grow obeying a logarithmic rule, or because of errors in estimating the geometrical parameters of the shell center (Rocha and Dias, 2003).

5. Discussion

Changes in dip of bedding from SE to NW in the northwestern limb of the Seydan anticline are related to variations of strain magnitude. Field studies show that along the northeastern limb of the Seydan anticline, the dip of folded beds gradually increases from southeast to northwest; toward the nose of the anticline, bedding dips vertically and eventually becomes overturned. According to Berberian (1995), the nature of reverse faulting has an important control on the geometry of Zagros anticlines, and many of the anticlines in the Zagros Fold-and-Thrust Belt are related to thrust faulting. Therefore, the geometry of anticlines is affected by the geometry and amounts of slip on associated reverse fault surfaces. The amount of slip on the fault is an important factor in the shape of the axial surface and the attitude of bedding planes in the limbs of folds (Twiss and Moores, 1992). Structural evidence shows that different amounts of slip on the Sivand thrust fault acted as an effective factor related to the variation in deformation and dip changes of bedding in the northeastern limb of the Seydan anticline. Increasing the dip of bedding and ultimately overturning beds along the northeastern limb of Seydan anticline implies a relative increase of slip from the southeast to the northwest on the Sivand thrust fault. Fig. 5 shows schematic cross sections along A, B and C directions (Fig. 2b), which display that an increase of deformation is probably related to different amounts of slip on the Sivand thrust fault.

For strain determination and comparing the results with qualitative structural evidence, we used Cretaceous fossil ammonites in the Sarvak Formation as strain markers. In this study, markers with low competency contrast relative to the matrix material, such as quartz pebbles and quartz grains in deformed conglomerate or sandstone, and ooids in limestone, are suitable strain markers. In the study area, ammonoid shells show filling by sediment or crystals of similar composition with the surrounding host rock and therefore, it is assumed that ammonoids have suffered homogeneous strain. Seven ammonite shells (S1–S7) were selected from the northeastern limb of the Seydan anticline and data was gathered from each sample. Fig. 2b shows the location of samples on
a geological map. Photographs of fossil shells were provided and the required components for quantitative measurements of strain were calculated with AutoCAD software. As mentioned, determination of the initial spiral angle ($\alpha$) of undeformed fossils is one of the main requirements in the strain analysis of spiral shells. According to Tan (1973), the spiral angle of the Jurassic and Cretaceous ammonite shells show the ranges between $80^\circ$ and $84^\circ$. Measurements of the spiral angles of undeformed ammonite shells from the study area gave a spiral angle ($\alpha$) of approximately $84^\circ$. At least 10 measurements of $\theta \pm (90^\circ - \alpha)$ and $\Psi \pm (90^\circ - \alpha)$ angles were performed for each ammonite shell. For this purpose, the direction of maximum length of the deformed ammonoid (red lines (X) in Fig. 6), radius (blue lines in Fig. 6) and tangent to the spiral shells were determined. Then, perpendicular lines to the tangent to the spiral were drawn. Finally, angles between the radius of the spiral and the direction of the maximum length of the deformed shells were determined. According to Fig. 7, strain measurement of deformed spiral shells (S1–S7) with application of graphical function (Tan, 1973) for initial spiral angle ($84^\circ$).

Fig. 7. Strain measurement of deformed spiral shells (S1–S7) with application of graphical function (Tan, 1973) for initial spiral angle ($84^\circ$).

1 For interpretation of color in Fig. 6, the reader is referred to the web version of this article.
ammonoid $\theta \pm (90^\circ - \alpha)$ and angles between the perpendicular to the tangent line and radius of the spiral $\Psi \pm (90^\circ - \alpha)$ were calculated, according to the clockwise or counterclockwise direction of these angles. Fig. 6 shows the measurements of $\theta \pm (90^\circ - \alpha)$ and $\Psi \pm (90^\circ - \alpha)$ angles for sample S4. The red line (X) and blue line show the direction of the elongated axes of the fossil and the spiral radius vector, respectively. With application of the strain method described above, and using a graphical function for the initial spiral angle ($\Psi_a$), the amount of strain was then calculated for each sample (Fig. 7). Plotting of $\Psi \pm (90^\circ - \alpha)$ and $\Psi \pm (90^\circ - \alpha)$ data for all samples shows that points fall onto curves with increasing curvature from S1 to S7, respectively, showing that the strain magnitude has increased from SE to NW (S1 to S7) along the NE limb of the Seydan anticline (see Fig. 8).

6. Conclusion

Quantitative strain analysis using strain markers are important tools to complement qualitative structural studies. In this study, a comparison of the numerical results of strain analysis and qualitative structural observations show a connection between a strain increase of measured ammonite shells and an increase in the dip of folded beds along northeastern limb of the Seydan anticline. This strain increase is interpreted to be due to different amounts of shear strain on the Sivand thrust fault, which is considered to be a consequence of lateral fold- and fault-growth mechanisms. Increasing strain as recorded by spiral ammonoids along the north-east limb of Seydan anticline from SE to NW (S1 to S7) confirms this relationship.

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