Journal of Structural Geology 31 (2009) 691–706

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Kinematic vorticity flow analysis and $^{40}Ar/^{39}Ar$ geochronology related to inclined extrusion of the HP–LT metamorphic rocks along the Zagros accretionary prism, Iran

Khalil Sarkarinejad [a,*], Laurent Godin [b], Ali Faghih [a]

[a] Department of Earth Sciences, College of Sciences, Shiraz University, Shiraz 71454, Fars Iran
[b] Department of Geological Sciences and Geological Engineering, Miller Hall, Queen's University, Kingston, Ontario K7L3 NG, Canada

ARTICLE INFO

Article history:
Received 14 July 2008
Received in revised form
18 March 2009
Accepted 12 April 2009
Available online 18 April 2009

Keywords:
Zagros accretionary prism
Zagros thrust system
Melange
Kinematic vorticity number
Iran

ABSTRACT

The Zagros accretionary prism in southwestern Iran is exposed along the NW–SE trending of the Zagros Thrust System and inclined Zagros transpression zone. This accretionary prism consists of two units: the upper sedimentary mélange unit on top and the high-pressure metamorphic mélange unit at the bottom. Both units show characteristics of a tectonic wedge. The upper unit consists of type-I, II and III mélanges which display S-, C- and C′-type shear-band cleavages, quartz ribbons and rectangular or fish-head boudins. The lower unit fabrics display σ-, and δ-type porphyroclasts and quartz ribbon mylonites. These fabrics formed from a combination of 60.5% simple shear and 39.5% pure shear. Both components were involved in a lateral exhumation of the high-pressure/low-temperature metamorphic rocks in an inclined transpression wedge-shaped geometry. The estimated kinematic vorticity number (W_k) was calculated from quartz *c*-axis patterns, rotation of porphyroclasts and orientation of finite strain with respect to shear zone boundaries. Using the mean estimated W_m value of 0.84, the inclination angle for the thrust wedge on top of the NE-subducting Neo-Tethyan oceanic lithosphere is 18°. The $^{40}Ar/^{39}Ar$ plateau ages of early generations of biotite from the lower metamorphic mélange are 119.95 ± 0.88 Ma and 112.58 ± 0.66 Ma. This late Aptian age is related to early thrusting and formation of HP–LT metamorphic rocks. The dating of two amphibole samples from the amphibolite yields a weighted mean age of 91.23 ± 0.89 Ma. This Turonian–Cenomanian age suggests a later metamorphic event associated with subduction and obduction of the Neyriz ophiolite and later lateral extrusion of HP–LT metamorphic rocks along the inclined Zagros accretionary prism.

1. Introduction

Most accretionary prisms form wedge-shaped structures bounded by a roof thrust along their upper surface and a floor thrust beneath (Chi et al., 2003. In such wedge-shaped structures the convergence direction is oblique or inclined, and the zone boundaries are non-planar (Jones et al., 2004; Sarkarinejad, 2007; Sarkarinejad and Azizi, 2008). During oblique or inclined transpression, there is tendency for pure-shear and simple-shear strain components to occur in spatially separated domains (Fossen et al., 1994; Tikoff and Teyssier, 1994; Teyssier et al., 1995; Jones and Tanner, 1995). Fossen and Tikoff (1993) divided transpression into pure-shear dominated and simple-shear dominated, depending on the angle of convergence as defined by infinitesimal strain axes. These two cases can be differentiated using the kinematic vorticity number W_k (Fossen and Tikoff, 1993), which is a non-linear ratio of the pure-shear to simple-shear component (Tikoff and Teyssier, 1994). There is an angular relationship θ between the maximum horizontal axis of the instantaneous strain ellipsoid and the boundary zones (Fossen and Tikoff, 1993). The angle θ is also related to α, the angle of oblique plate convergence or flow apophysis (Tikoff and Teyssier, 1994). Based on theoretical modeling, Fossen and Tikoff (1993) suggested that simple-shear dominated transpression occurs when $1 > W_k > 0.81$ and $35° < \theta < 45°$ whereas pure-shear dominated transpression occurs when $0.81 > W_k > 0$ and $0° < \theta < 35°$.

Strain matrix modeling of transpressional deformation shows that all three axes of the finite strain ellipsoid are non-parallel to the Cartesian reference frame which experiences complex non-planar rotations during ongoing deformation (Jones et al., 2004). The maximum finite strain axis and material lines are always "attracted" to the extensional flow apophysis (or maximum extensional flow direction) (Fossen et al., 1994; Passchier, 1997).

* Corresponding author. Tel.: +98 711 8321348; fax: +98 711 2284572.
E-mail addresses: sarkarinejad@geology.susc.ac.ir (K. Sarkarinejad), godin@geol.queensu.ca (L. Godin), afaghih@shirazu.ac.ir (A. Faghih).

0191-8141/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2009.04.003

Consequently, a relation exists between the orientation of strain/fabric and principal flow directions (Teyssier and Tikoff, 1999). Theoretical modeling predicts that the maximum finite strain axis or stretching lineation switches from horizontal to vertical with increasing strain (monoclinic transpression; Sanderson and Marchini, 1984) or when the stretching lineation lies almost strike-parallel or is significantly oblique or approximately down dip (triclinic transpression; Jones and Holdsworth, 1998; Jones et al., 2004). In all of these models, idealized boundary conditions are assumed, as defined by Sanderson and Marchini: deformation is homogeneous, constant volume, laterally and basally confined, and occurs between parallel zone boundaries (Jones et al., 2004).

Accretionary prisms form marginal boundary zones in which the deeply subducted and "transpressed" rocks act as viscous materials squeezed between two inclined rigid plates. This paper describes structures and microstructures related to real transpressional zones to test the applicability of the simplified stain matrix modeling. The objectives of this paper are: (1) to describe the dominant fabrics identified in the upper sedimentary and lower metamorphic mélanges, (2) to investigate the *c*-axis preferred orientations from quartz ribbons, (3) to estimate the kinematic vorticity number for quantifying pure-shear and simple-shear components, (4) to use geochronology to obtain absolute ages for the deformation events.

2. Geology of the Neyriz area

The Neyriz area is located in southwestern Iran. This area has an excellent exposure of the Neyriz ophiolite, the Zagros thrust system, the Hassan Abad upper sedimentary tectonic mélange, the Seh-Ghalatoun lower metamorphic tectonic mélange and the HP–LT/HT–LP Sanandaj-Sirjan paired metamorphic belts (Fig. 1). The Zagros orogenic belt is the central part of the Alpine–Himalayan mountain chain. This orogenic belt extends for more than 2000 km in a NW–SE direction from eastern Turkey to the Minab-Zendan fault system in southern Iran (Haynes and McQuillan, 1974; Stocklin, 1974. This belt resulted from the closure of the Neo-Tethyan Ocean due to northeast-dipping subduction below the Iranian microcontinent (Alavi, 1994; Vernant et al., 2004).

The geodynamics of the region are dominated by the convergence between the Arabian and Eurasian plates (Jackson and Mckenzie, 1984). Compressional structures related to the closure of the Neo-Tethyan Ocean (e.g. Stocklin, 1968; Falcon, 1974; Berberian and King, 1981; Alavi, 1994) strike oblique to the convergence direction. This obliquity is probably due to the pure-shear dominated transpression and shortening accommodated by imbricate thrusting as well as oblique extrusion of deeply subducted high-grade metamorphic rocks (Sarkarinejad, 2003, 2005, 2007; Sarkarinejad and Azizi, 2008).

2.1. Structure of the Neyriz ophiolite

The Neyriz ophiolite (Fig. 1), exposed in the southwestern part of the Sanandaj-Sirjan metamorphic belts, is considered to consist of allochthonous fragments of the Tethyan Oceanic crust and mantle (Gansser, 1974; Stocklin, 1968). The Neyriz ophiolite has been thrust over the Pichkun formation, consisting of abyssal sedimentary facies containing radiolarian cherts, fossiliferous limestone, turbidite, middle Jurassic oolitic and micro-brecciated limestone, and middle Cretaceous limestone (Ricou, 1968).

The Neyriz ophiolite is probably the largest, best exposed, and best-preserved example of oceanic lithosphere in Iran (Sarkarinejad, 2005). It includes the entire thickness of the deformed mantle section, from the ultramafic Moho Transition Zone (MTZ), to the mafic section which includes gabbros, sheeted dikes and pillow lavas, and to radiolarian cherts on top. The deformed mantle section (6 km thick) mostly consists of harzburgite, serpentinized harzburgite and lherzolite. In thin section the harzburgite shows coarse- to medium-grained porphyroclastic fabrics (Sarkarinejad, 2005). High-temperature (HT) deformation of the coarse-grained granoblastic structures is related to hypersolidus or solidus temperatures (1200°–1250 °C), and thus to large-scale plastic flow below the oceanic ridge. Medium-temperature (MT; 1100 °C) deformation is related to localized motion along shear zones and detachment thrusts (Nicolas et al., 2000). Construction of mantle flow trajectories based on detailed structural mapping of the Neyriz mantle section reveals three mantle diapirs aligned along the NW–SE direction (Sarkarinejad, 2005). They are characterized by steep foliations in the high-temperature harzburgite and an associated steeply dipping stretching lineation, reflecting localized vertical flow related to mantle diapirs (Sarkarinejad, 2005).

The Moho Transition Zone (MTZ) is composed of dunite, chromite clinopyroxenite and websterite. The clinopyroxene, orthopyroxene and olivine minerals of the MTZ are moderately deformed. Low-level layered gabbros are exposed on top of the MTZ. The normal sequence of the sheeted dikes, pillow lavas, overlying lava flows and radiolarian cherts is best exposed in the central part of the ophiolite sequence (Sarkarinejad, 2005). The sheeted dike complex is uniformly steep, inclined 66°–89° with a mean dip direction N 47° W, 67° NE (Sarkarinejad, 2005). The average orientation of the sheeted dikes is vertical and parallel to the paleo-ridge axis (Nicolas, 1989).

3. Mélange

The mélange outcrop is located in the east to northeastern part of the Neyriz ophiolite and extends along the Zagros thrust system (Fig. 1). The mélange is divided into two units based upon: (1) the lithology and origin of the blocks and surrounding matrix; (2) intensity of deformation and degree of metamorphism; (3) number of phases of deformation.

The upper Hassan Abad sedimentary mélange (Fig. 1) is exposed as a narrow shear zone along the Zagros thrust system. The mélange length extends approximately 53 km and its width varies from 250 to 3750 m. Excellent exposures of mélange are preserved in the road cuts along the Hassan Abad and Naghare-Khaneh passes. The mélange consists of lenses, blocks and/or ribbons of radiolarian cherts, limestone, sandstone, pillow lava, tuff, and serpentinite, in a matrix of shale, greywacke and mudstone (Sarkarinejad, 2003). The mélange lenses or blocks range in size from millimeters to several hundred meters. The sedimentary mélanges can be classified according to their fabrics; they include type-I, type-II and type-III tectonic mélanges.

3.1. Type-I mylonite mélange

The upper sedimentary mélange unit is a type-I mylonitic mélange. Three types of shear-band cleavages were distinguished in this mélange; C-type C′-type and S-type shear-band cleavages (Fig. 2A) corresponding to the C- and S-bands of Berthe et al. (1979a,b). The C-type is an extensional cleavage and is part of an S/C fabric that consists of S-planes transected by distinct planar C-type shear bands or C′-planes (Berthe et al., 1979a,b; Lister and Snoke, 1984). The angle between the C- and S-planes is 35°. The angle between the C- and C′-planes is 45°.

On the microscopic and mesoscopic-scales, porphyroclasts consist of fragments of sandstone, limestone, pillow lavas and