

## Dating of Precambrian Metasedimentary Rocks and Timing of their Metamorphism in the Soursat Metamorphic Complex (NW IRAN): Using LA-ICP-MS, U-Pb Dating of Zircon and Monazite

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### Abstract

Soursat Metamorphic Complex (SMC) in west of Takab city is one of the polyphase metamorphic terranes in northern Sanandaj-Sirjan metamorphic belt of Iran. The SMC composed mainly of metasedimentary rocks associated with granitic intrusions. Based on metamorphic rocks, two metamorphic phases could be separate in the complex. M1 is representative of regional metamorphisms which varies from greenschist to amphibolite facies and consists of mica-schist, garnet-schist, staurolite-schist, kyanite-schist, fibrolite-schist, garnet amphibolites, marble, gneiss. M2 is contact metamorphism with clear outcrop just in the central of SMC and overprinted on M1. This phase consists of andalusite-schist, cordierite-schist and Actinolite-schist. SMC is in tectonic contact with Precambrian to Paleozoic sedimentary rocks which make it difficult to date it based on stratigraphy. In this study, U-Pb dating of zircons and Monazites used in order to find the ages of deposition and metamorphism of metasediments in SMC. U-Pb dating of zircons from a staurolite-schist in the complex by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) yielded a maximum Precambrian depositional age of  $605 \pm 43$ . Monazites were also dated from a garnet-schist using the same technique and yielded a  $^{238}\text{U}/^{206}\text{Pb}$  age of  $61 \pm 8$  which is interpreted as the age of the regional metamorphism. Based on these ages, metasedimentary protoliths of the SMC are deposited at the same time as the surrounding essentially unmetamorphosed Precambrian-Cambrian sedimentary rocks and regional metamorphism occurred later in Paleocene and could be related to the orogenesis during the collision of Arabian plate with Iranian block and closure of Neotethys.

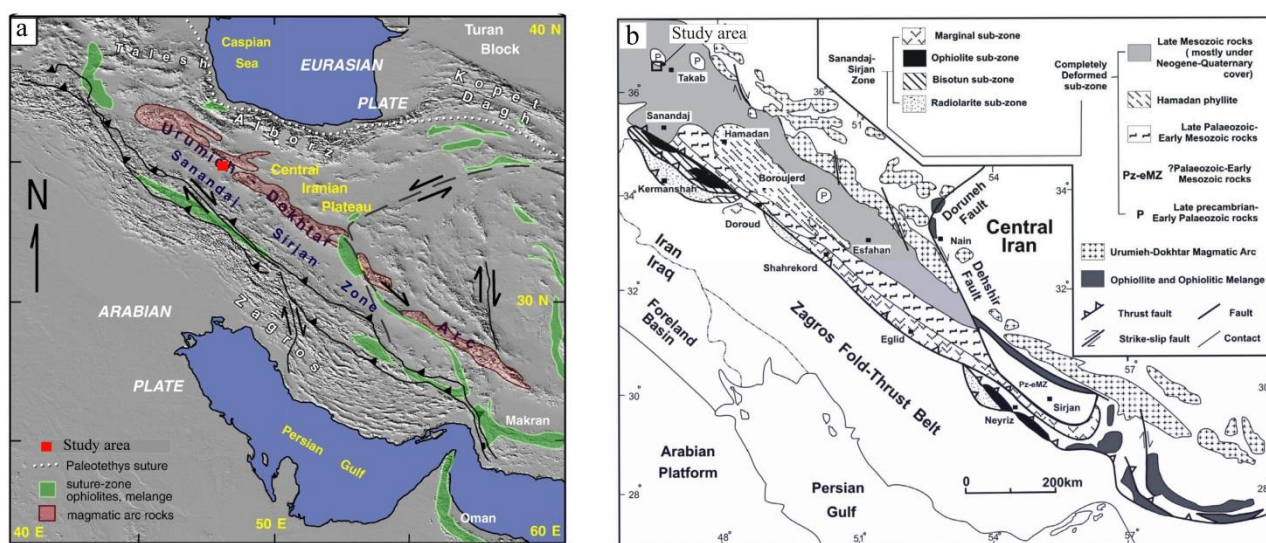
**Keywords:** LA-ICP-MS Dating; Precambrian; Soursat Metamorphic Complex; Takab

### Introduction

Sanandaj-Sirjan Zone (SSZ) in Iran is a metamorphic

zone which was exhumed subsequent to collision between accreted the Afro-Arabian continent and the Iranian microcontinent terranes. Subduction of the

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**Figure 1.** (a) Geologic map of Iran and surrounding regions showing mountain belts, Zagros fold-thrust belt (after [15]). Red square indicates study area (b) Location of the Sanandaj-Sirjan belt in Iran and black square shows the study area (after [35]).

Tethyan sea floor under Central Iran along the Sanandaj-Sirjan Zone initiated prior to the Late Cretaceous/Paleocene [5,30,31,34,35], or about 20 million years, in the latest Eocene [3,4]. Sanandaj-Sirjan zone acting as a deformable backstop [48] and is a region of polyphase deformation which the youngest one recorded the collision [1]. The grade of metamorphism in SSZ is reported to be mainly greenschist and lower to upper amphibolite facies [e.g. 6, 34 and 44]. However, high-pressure metamorphism is also observed [12].

The Soursat Metamorphic Complex (SMC) is one of the polyphase metamorphic terranes in northern Sanandaj-Sirjan Metamorphic belt of Iran (Fig. 1). SMC is in tectonic contact with Precambrian to Paleozoic sedimentary rocks (Kahar, Bayandor, Soltaniyeh, Barut, Lalun and Mila formations) which make it difficult to date it based on stratigraphy. The age of Soursat Complex was first reported in the Shahin Dezh geological map (scale 1:250000) [2], where it was tentatively assigned a Precambrian age (see also [16, 17, 37]) and viewed as analogous to the Precambrian basement rocks exposed in the Arabian shield (e.g., [48]). Previous attempts at dating rocks within the SMC (Pichagchi pluton) have employed the K-Ar technique and yielded an age of ~75 Ma [26]. This age has directly influenced palaeogeographic and plate tectonic reconstructions [27], yet its significance is far from clear. However, the association of granitoids with old basement in SMC, also suggesting that plutonism could

not be entirely related to the events which formed SSZ during Subduction of the Tethyan Sea.

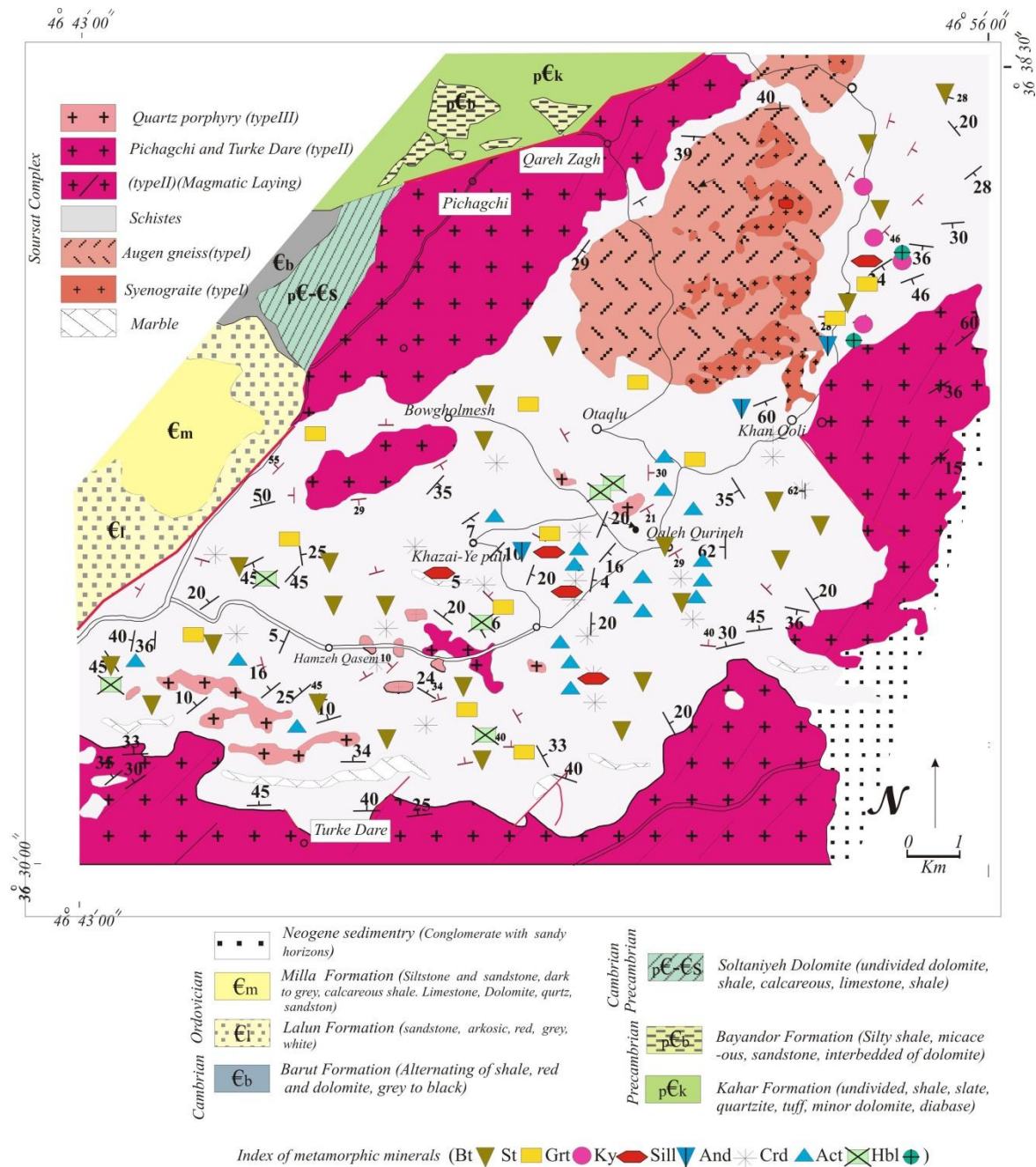
This research is focused on U-Pb Laser Ablation ICP-MS dating of metasedimentary rocks and timing of their metamorphism in the SMC. Modern U-Pb Laser Inductively Coupled Mass Spectrometry (LA-ICP-MS) for zircon is the preferred methods for determining deposition ages of metasedimentary due to the closure temperature of the U-Pb system well in excess of the solidus 700–750 °C and the refractory nature of zircon and U-Pb Laser Inductively Coupled Mass Spectrometry (LA-ICP-MS) for monazite is the preferred methods for determining metamorphism. The results could apply to constrain the sequence of the events and evolution of northern SSZ.

## Materials and Methods

### Geological Setting

SMC have been studied since the term was introduced by Pelissier [41] and Darvishzadeh [9], because of the presence of different metamorphic rocks, granitoids and its tectonic settings. Geology of complex reviewed in detail by many researchers (see e.g. [2, 13, 14, 22, 23, 24, 26, 27, 29, 30 and 33]).

SMC formed by metasedimentary, metavolcanosedimentary rocks and associated granitic intrusions. The complex presents tectonic contact with nearby sedimentary rocks. Two main geological units have



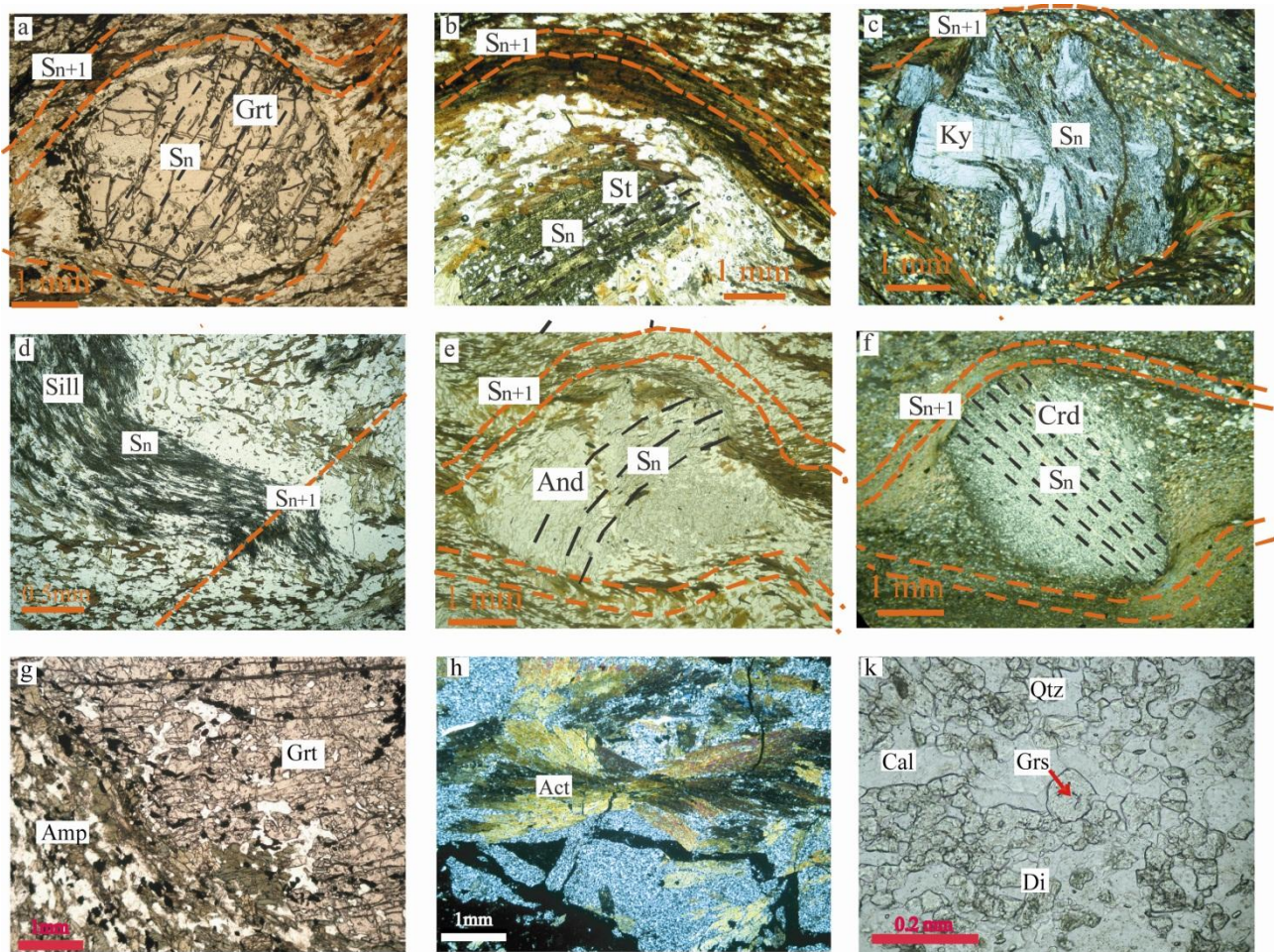
**Figure 2.** Simplified geological map of the SMC, showing distribution and mineral assemblages of metamorphic rocks and main outcrops of different granitoids.

been described for Precambrian to Paleozoic sedimentary rocks [27]: (1) upper Precambrian Kahar formation consisting of slate, sandstone and some acidic volcanic rocks those locally reveal a very low metamorphic grade, and (2) Precambrian-Cambrian and Ordovician dolomite (Kahar, Bayandor and Soltaniyeh formations), sandstone, shale and dolomitic limestone

(Barut, Lalun and Milla Formations) (Fig. 2).

Metamorphic rocks are mainly mica-schist, garnet-schist, staurolite-schist, kyanite schist, fibrolite schist, andalusite-schist, cordierite-schist, Actinolite schist, marbel, garnet amphibolites, gneiss and granite-gneiss (Fig. 3).





**Figure 3.** Microphotographs showing different metamorphic rocks and representative textural relationships in metapelites of SMC. a) Garnet porphyroblast with Sn inclusion trails, that is defined by quartz and opaque minerals. Biotite and quartz (Sn) in matrix is crenulated (Fn+1). Crenulations deflect the garnet porphyroblast; b) Staurolite porphyroblast with Sn inclusion trails which defined by quartz and opaque minerals. Muscovite and quartz (Sn) in matrix is crenulated (Fn+1). Crenulations deflect the staurolite porphyroblast; c) Kyanite with Sn inclusion trails which are defined by quartz and opaque minerals and external Crenulations (Sn+1) deflect the internal schistosity (Sn); d) Sillimanite (fibrolite) porphyroblast with Sn inclusion trails that are defined by quartz and opaque minerals. Muscovite and quartz (Sn) in matrix is crenulated (Fn+1); e) Andalusite with Sn inclusion trails that are defined by quartz and opaque minerals and external Crenulations (Sn+1) deflect the internal schistosity (Sn); f) Cordierite porphyroblast with Sn inclusion trails that is defined by quartz, biotite, muscovite and opaque minerals and external Crenulations (Sn+1) deflect the internal schistosity (Sn); g) Photomicrograph of garnet porphyroblast in garnet-bearing amphibolite rock (long dimension up to 6 mm). Garnet contains inclusions of ilmenite and quartz also present in the matrix; h) Actinolite schist with fan type texture that outcrop in central of SMC; k) marble with diopsid, grossular, calcite and quartz. (Gr, garnet; St, staurolite; Ky, kyanite; Sill, sillimanite; And, andalusite; crd, cordierite; Am, amphibolite; Act, Actinolite; Grs, grossular; Di, diopsid; Cal, calcite; Qtz, quartz).

### Laser Ablation ICP-MS Dating

ICP-MS dating of Zircon and monazite crystals in two schists were obtained on University of Adelaide based on following basics. Zircons were separated using conventional methods that include crushing, sieving, magnetic separation and floatation. More than fifty zircon grains were handpicked under a binocular

microscope. The zircons were then set in synthetic resin mounts, polished and cleaned in a warm  $\text{HNO}_3$  ultrasonic bath. Cathodoluminescence (CL) and back-scattered electron (BSE) imaging were carried out to help characterize any compositional variation within individual zircons. Equipment and operating conditions for zircon analysis were identical to those reported by Payne *et al.* [40]. A spot size of 30  $\mu\text{m}$  and repetition

rate of 5 Hz was used for U–Pb data acquisition, producing a laser power density of ~8 J/cm<sup>2</sup>. Zircon ages were calculated using the GEMOC GJ-1 zircon standard to correct for U–Pb fractionation (TIMS normalization data <sup>207</sup>Pb/<sup>206</sup>Pb=608.3 Ma, <sup>206</sup>Pb/<sup>238</sup>U = 600.7 Ma and <sup>207</sup>Pb/<sup>235</sup>U = 602.2 Ma — [21]), and the GLITTER software for data reduction [50]. Over the duration of this study the reported average normalized ages for GJ-1 were 609±10, 600.2±2.7 and 601.9±2.4 Ma for the <sup>207</sup>Pb/<sup>206</sup>Pb, <sup>206</sup>Pb/<sup>238</sup>U and <sup>207</sup>Pb/<sup>235</sup>U ratios, respectively (n=24).

Metamorphic monazite from sample Sh-68 was imaged using backscattered electron imagery (BSE) and conducted by LA-ICPMS at the University of Adelaide. Equipment and operating conditions for monazite analysis are identical to those reported by Payne et al. [39, 40]. U– Pb acquisition utilized 10 µm beam diameter for monazite run at a repetition rate of 5 Hz. Monazite ages were calculated using the MADEL monazite standard to correct for U– Pb fractionation (TIMS normalisation data: <sup>207</sup>Pb/<sup>206</sup>Pb=490.7 Ma, <sup>206</sup>Pb/<sup>238</sup>U=514.8 Ma, <sup>207</sup>Pb/<sup>235</sup>U=510.4 Ma: [39]), and again the GLITTER software for data reduction. Over the duration of this study, the reported average normalised ages for MADEL are 493.0±8.3, 514.3±2.4 and 511.2±2.0 Ma for the <sup>207</sup>Pb/<sup>206</sup>Pb, <sup>206</sup>Pb/<sup>238</sup>U and <sup>207</sup>Pb/<sup>235</sup>U ratios, respectively (n=32). Accuracy was monitored by repeat analyses of the in-house internal monazite standard (94–222/ Bruna-NW: <sup>206</sup>Pb/<sup>238</sup>U=447 Ma: [39]). Over the duration of this study, the reported average <sup>206</sup>Pb/<sup>238</sup>U age for the internal standard was 446.9±3.1 Ma (n=15).

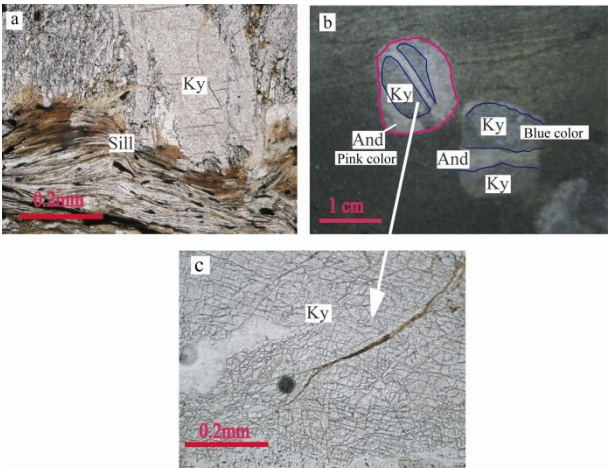
## Result and Discussion

### Metamorphic Rocks of SMC

Metapelitic rocks in SMC contain garnet, staurolite, kyanite, fibrolite, cordierite and andalusite. Porphyroblasts in schists have the same petrofabric and three schistosity are present. The internal schistosity (Sn) inclusion trails are also offset by conjugate sets of extensional schistosity (Sn+1) and (Sn+2) made crenulations on (Sn+1) (Fig. 3). The same texture of cordierite and andalusite with garnet, staurolite, kyanite and fibrolite porphyroblast formed during the same deformation phase and related to regional folding that reported by Ghasemi [13], Jamshidi badr [24] and Masoudi [30] in SMC. However, the minerals aren't paragenesis [24]. Metapelitic rocks in the SMC have previously been separated into the kyanite- and andalusite-types. The kyanite-type involves of biotite, garnet, staurolite, kyanite, Sillimanite which refer to

regional metamorphic (M1) with medium P-T. The andalusite-type includes biotite, cordierite and, locally, Staurolite. Actinolite schists are also present as metabasic rocks and are refer to contact metamorphic phase (M2) with high T-low P [24].

Assemblage of M1 metamorphic phase is present in

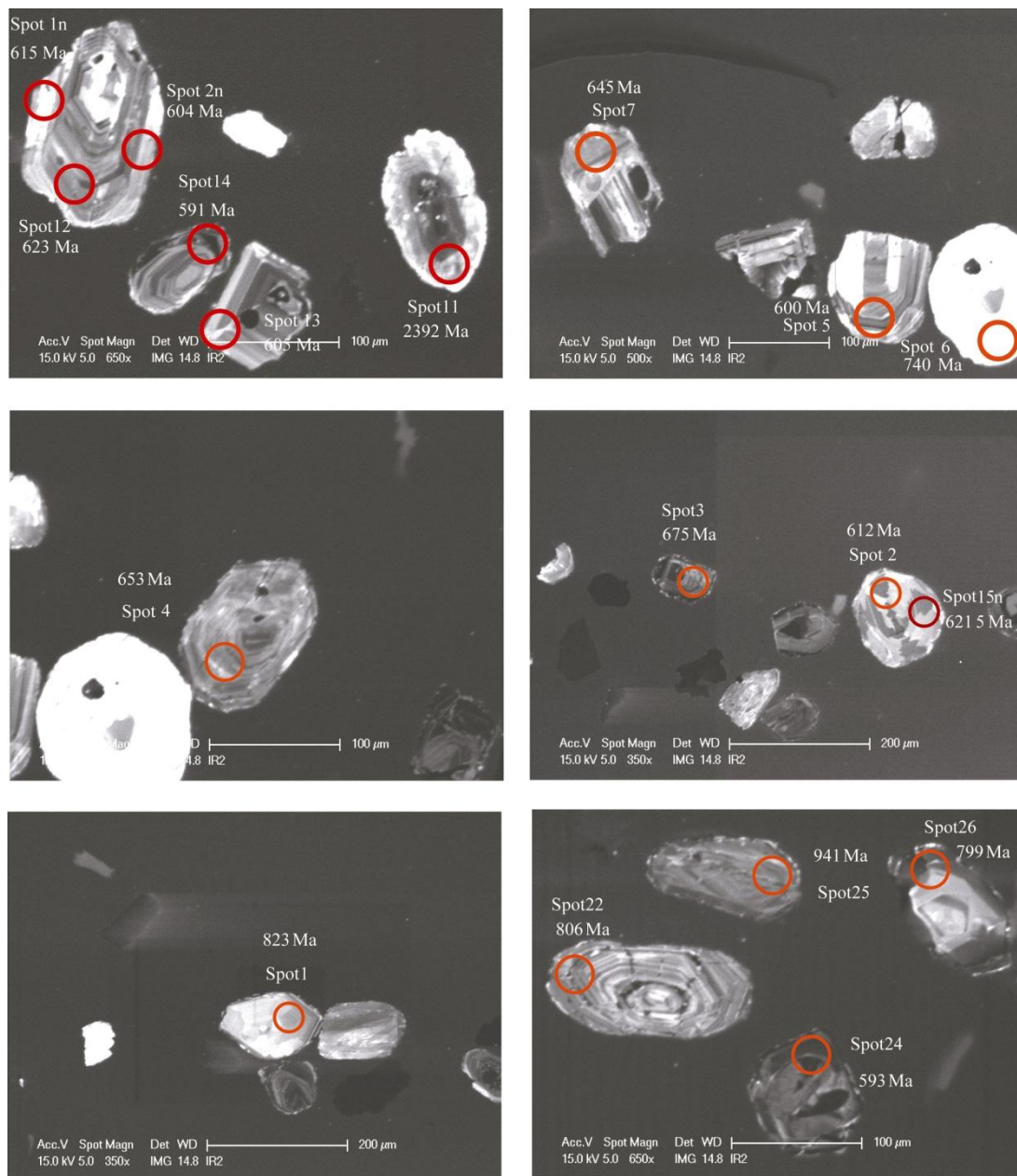


**Figure 4.** Photographs showing the textural relationships of aluminosilicates in SMC metapelites (PPI). (a) Kyanite porphyroblast with high relief and sillimanite (fibrolite); (b) Kyanite porphyroblast with unstable surrounding in mesoscopy scale, the core is kyanite with blue color and surrounding is andalusite with pink color; (c) Kyanite porphyroblast with perfect two cleavages (PPI).

Schistosity	Sn Continuous Foliation	Sn+1 Crenulation Cleavage	Sn+2 Crenulation Cleavage Local Shear Zone
Deformation	Dn	Dn+1 Regional folding	Dn+2
Minerals			
Grt			
St			
Ky			
Sill			
And			
Crd			
Act			
Ms			
Bt			
Metamorphism phases	M1 Syn to post Sn Pre Sn+1	M2 Post Sn pre Sn+1	
Age(Ma)	~60	younger than M1	

**Figure 5.** Appearance of metamorphic minerals in relation to different deformational events, timing and metamorphism phases.





**Figure 6.** CL images of Zircon analyzed and some analyzed spots from Sh-161.

many parts of SMC (Fig. 2), but assemblage of M2 metamorphic phase is just outcrops close to the quartz porphyry intrusions (Type III), which is represented by porphyritic granite and leucogranite and forms an outcrop in the central part of the complex. A thermal aureole around the Type III intrusions affected the previously regionally metamorphosed schists. The heat of the intrusion was a foundation for the development of andalusite and cordierite in the host metapelite schists

and actinolite in the host metabasic schists (Fig. 2). Typical Fan types actinolite grow in high T and Low P metamorphism [7, 38] and fan types actinolite in SMC are related to M2 metamorphism (Fig. 3h).

On the basis of a reevaluation and petrography of phase relations in kyanite and andalusite-bearing rocks, Kyanite was first crystallized Al-silicate in SMC. Porphyroblasts of Kyanite with two cleavages are present in core and surrounded by andalusite and

occasionally sillimanite (fibrolite) in mesoscopy and microscopy scales (Fig. 4). Kyanite is unstable with cordierite assemblages and has partially replaced by sillimanite (fibrolite) and andalusite. Recent studies on similar features in metamorphic complexes reported the metastable nature of these parageneses and attributed to presence of two metamorphic stages [25,32,42,53]. Regional folding in SMC occurred after two metamorphic stages (M1, M2), and porphyroblasts show the same petrofabric, but they aren't related to same metamorphic phase and paragenesis [24,30] (Fig. 5).

### U – Pb Dating

#### Age Constraints of Deposition

Sample (Sh-161) from the schists was collected about 2 km east of the village of Qareh Zagh (N36°35'43", E46°52'29") for dating. Metamorphic mineral assemblages of metasedimentary in sample Sh-161 include staurolite, cordierite and andalusite. The sample was collected from a ~2 m-thick outcrop in the central region of SMC. This sample has got M1 staurolite and M2 cordierite, and we tried to obtain two different groups of metamorphic zircons representative for two different metamorphic ages. However, there wasn't any metamorphic zircon (Fig. 6) and their data make up depositional age for the original sedimentary protoliths. It was dated using the LA-ICP-MS at the University of Adelaide. Zircons from this sample are light brown, prismatic, up to 150  $\mu\text{m}$  long, and generally euhedral. CL images show obvious oscillatory zoning (Fig. 6). A weighted mean of the  $^{206}\text{Pb}/^{238}\text{U}$  ages from the youngest six >90% concordant analyses produced an age of  $605 \pm 43$  Ma.

This sample contains evidence for a considerable Palaeoproterozoic detrital input into their original sedimentary make up depositional age for the protoliths with constrained age between ~1000 and ~600 Ma (between the youngest reliable detrital zircon and the oldest reliable detrital zircon respectively). With the presented ages, protoliths of metasedimentary rocks of the Soursat Metamorphic Complex are interpreted to be deposited at the same time as the surrounding essentially unmetamorphosed Precambrian-Cambrian sedimentary rocks.

#### The Age of Metamorphism

Sample Sh-68 was obtained from a ~2 m-thick outcrop of coarse-grained garnet – biotite – quartz metapelitic exposed in northwest of SMC close to the Dowlangaz village. Monazite from this sample was analyzed to determine the time of metamorphism (M1)

from Sn schistosity within the complex. The majority of grains are homogeneous under BSE (Fig. 7). A weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  is age of  $61 \pm 8$  Ma obtained.

Metamorphic monazite U–Pb data often show a 1–30 Ma inter- and intra-crystalline age variation (e.g. [8, 11, 12, 19 and 46]). This Variation related to the episodic growth/recrystallisation of monazite during prograde metamorphism. We could accept the age of ~60 Ma as the time of the first metamorphic phase on the SMC.

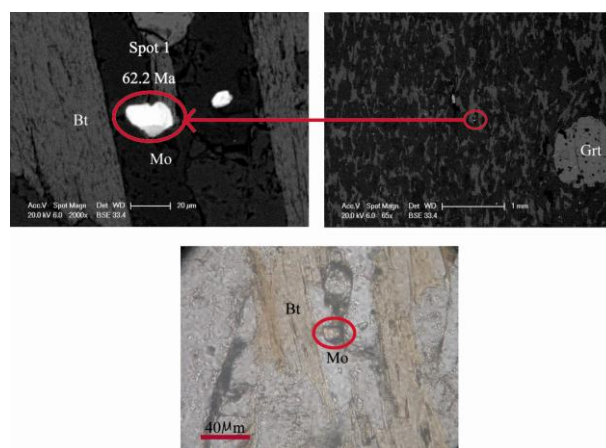
#### The Age of Metasedimentary Rocks and Time of their Metamorphism

The presence of Precambrian Iranian basement first reported in Shahin Dezh geological map (scale 1:250000) [2]. The age of  $605 \pm 43$  Ma obtained during this study confirmed that protoliths of SMC formed at the same time as the surrounding unmetamorphosed Precambrian-Cambrian sedimentary rocks. We conclude that the SMC from Iranian block were originally part of a series which named Peri-Gondwanan terranes that reported in different regions in Iran [18,20,37,45,47] and turkey [49].

First metamorphic event in SMC was a regional metamorphism (M1) and occurred later in Paleocene. It could be related to the orogenesis during the collision of Arabian plate with Iranian block and closure of Neotethys.

Based on the dating, protolith of metasedimentary rocks in the SMC are related to the Precambrian-Cambrian. Primary basement rocks metamorphosed because of regional metamorphism (M1) during the Paleocene time.

This activity probably was responsible for exhumation of Neoproterozoic-Early Cambrian basement



**Figure 7.** Photographs of garnet schist (Sh-68). a) & b) BSE images of monazite analyzed; c) monazite (PPL).

at during the Paleocene time and made M1 metamorphism on Precambrian-Cambrian sedimentary rocks. This event is the same as other metamorphic core complexes in central Iran [51] and Sanandaj-Sirjan metamorphic zone [10, 36] that Verdel [52] related them to the roll-back event in Sanandaj-Sirjan zone.

Second metamorphic stage in SMC is contact metamorphism (M2) that related to the youngest intrusion on complex which its aureole overprinted regional metamorphism (M1).

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