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The Sungun porphyry magma resource and the 120,000-year difference in age between the main stock and the first dike: New evidence from $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$ and Pb, SHRIMP U–Pb zircon dating in NW Iran

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Abstract

The Sungun copper porphyry deposit is hosted by a Tertiary magmatic complex in the Azarbaijan province, northwestern Iran. The Sungun mine in its southern and eastern parts is limited by early Miocene volcanic and by Late Cretaceous limestone rocks in northern and eastern parts respectively. The Sungun deposit is associated with a suite of porphyritic granitoids and late dikes intruding within Oligo-Miocene andesitic and upper Cretaceous limestone. The Sungun porphyry system developed in multi-stage, central intrusive rocks of the early Miocene age in the Tertiary Arasbaran Magmatic Zone (AMZ). A late post-mineralized dike (DK1a) is the first dike system after the replacement of the Sungun porphyry. It has been dated with a 20.57 ± 0.27 Ma ($\pm 2 \sigma$). New zircon SHRIMP U–Pb data indicates that the Sungun porphyry crystallized within the time span from 20.69 ± 0.37 Ma ($\pm 2 \sigma$), and the Sungun porphyry and DK1a represent a near-dated intrusive with an age difference of about 0.12 Ma (120,000 y). Their range of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70467 to 0.72278), $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (0.51275 to 0.51214), $^{87}\text{Rb}/^{86}\text{Sr}$ (0.67497 to 0.67415 values), lead isotopes ranges from 18.67 to 18.86, 15.65 to 15.66, and 38.93 to 39.06 for the ratios of $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ respectively, suggest the high contributions of depleted mantle-derived magmas in the generation of Sungun stock, but crustal-contaminated origin for monzonitic body in late magmatic activities in the area. This study shows that the source of the Sungun stocks is categorized in the upper crust, typically similar to the source of porphyry deposits.

Keywords: Porphyry copper deposit, Sungun, Azerbaijan, NW Iran

1. Introduction

The Sungun porphyry copper deposit is one of the two major deposits associated with calc-alkaline intrusive rocks in the Tertiary Arasbaran volcano-plutonic zone, which extends north-westward from northwestern Armenia to the Sabalan area in the south-eastern part of the East Azerbaijan province of Iran (Fig 1). This is an area of approximately 15,000 km² (in just the Iranian part of the belt). The magmatic episode was an expression of Andean-type magmatism that developed along the continental margin in response to subduction processes to the south (Berberian et al. 1981; Hassanpour 2010, 2013; Ghaffari et al. 2015; Hassanpour et al. 2015; Sohrabi 2015). In order to establish difference crystallization age of Sungun stock with dike system intrusions, zircon U–Pb dating was carried. Ar–Ar dating of first stage dike intrusion, a post mineralization dike (DK1a) that intruded the Sungun porphyry is aim of the research, to compare it with the ages of the Sungun porphyry and the andesitic host rocks.

Furthermore, the precise age difference between the emplacement of the first-stage dike and porphyry system in the Arasbaran magmatic zone will support a Tertiary age for the mineralization.

2. Geological setting

The study area is located in the Alborz–Azarbaijan zone (Nabavi 1976), about 75 km NW of Ahar and 35 km North of Varzaghan towns, between longitudes 46° 41' to 46° 45' E and latitudes 38° 41' to 38° 43' N. The oldest rocks that were exposed in the study area are a 500-m-thick succession, consisting of intercalations of Cretaceous limestone and shale, and a 1,500m thick sequence of early Eocene to late Pliocene lavas of intermediate, calc-alkaline composition, and tuffaceous rocks, and numerous calc-alkaline andesite bodies. The Oligo–Miocene Sungun complex has been emplaced into Cretaceous limestone and Eocene tuffs and agglomerates of trachy-andesitic composition.

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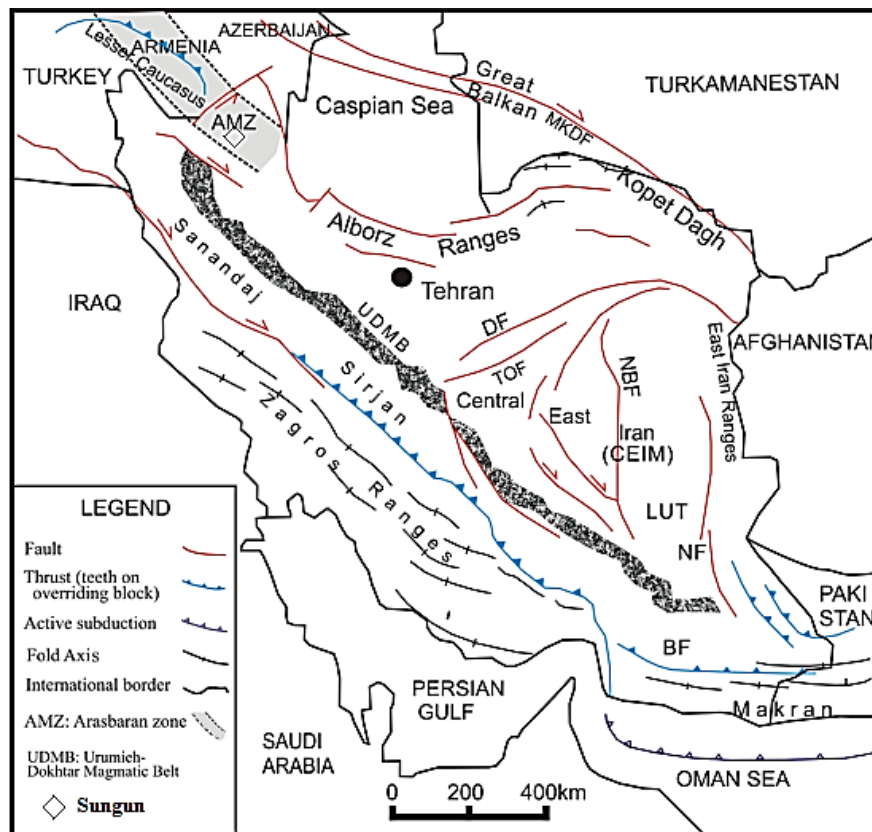


Fig 1. Simplified structural map of Iran (modified from Stocklin and Setudenia (1972)) showing major lithotectonic units: Zagros fold Belt: Paleozoic platform sediments overlain by miogeosynclinal Mid-Triassic to Miocene sediments and syn-orogenic Pliocene–Pleistocene conglomerates; Sanandaj–Sirjan zone: Dominantly Mesozoic metamorphosed sediments and granitoid intrusions; Central Iran Late Precambrian–Mesozoic continental shelf deposits overlying a Precambrian crystalline basement. Paleozoic horsts of Precambrian crystalline basement; Sahand–Bazman (Urumieh–Dokhtar) Belt Cenozoic dominantly calc-alkaline volcanic and intrusive rocks; Lut Block: An old stable platform covered by thick Mesozoic sediments and Eocene volcanics; Alborz Phanerozoic shelf sediments with periodic hiatuses on a Precambrian basement; active Cenozoic magmatism in southern Alborz; Kopet Dagh: Jurassic–Paleogene shelf sediments underlain by a Cimmerian metamorphic basement; East Iran: Dominantly Cenozoic volcanic and intrusive rocks; Makran: Post Cretaceous flysch-mollasse sediments.

The Sungun porphyry deposit occurs within an intrusive complex composed of multiphase diorite, granodiorite and monzodiorite porphyries, the main phase (granodiorite porphyry) of which has a 20.69 ± 0.37 Ma U-Pb zircon age (Hassanpour et al. 2015; Aghazadeh et al. 2015), and multiple phases of dikes of unknown age, which were emplaced into the Sungun complex, Cretaceous limestones, and andesitic volcanic rocks. These yielded a late Oligocene 27.65 ± 0.51 Ma U-Pb zircon age (Hassanpour et al. 2015). The main porphyry stock at the Sungun has a plan area of approximately 3.45 km^2 ($1.5 \times 2.3 \text{ km}^2$), is elongated in the NW–SE direction, and consists of three different phases (Fig 2), in order of emplacement: 1. Monzogranite/granodiorite; 2. diorite/monzodiorite; and 3. andesite/dacite and related dikes. The main porphyry stock has been intruded (with an early Miocene age as a granitoid stock (granodiorite to granite in composition)), into upper Cretaceous carbonates, and a basaltic to andesitic volcanic sequence hosting the ore deposit. Almost all the intrusive units contain the same mineral

assemblage of plagioclase, alkali-feldspar, quartz, biotite, hornblende (typically altered to biotite and/or chlorite), titanite, rutile, apatite, and with minor magnetite, and zircon (Hezarkhani 2006). The porphyry intrusion is cut by several dikes (DK1 [a, b, c], DK2, DK3 and DK4), ranging in composition from quartz monzonite to monzonite and diorite (Hamedi 2007; Calagari 1997). Hamedi 2007 suggested that the dike systems developed during a stage of shearing along the neighboring NW–SE trending, sinistral Sungun fault zone.

Between four types of cross-cutting dikes (DK1, DK2, DK3, and DK4), barring dike type DK1, the intrusions of the other types (DK2, DK3, and DK4) are post-mineralization events based on pyritization (Calagari 1997; Hamedi 2007). However, this research has revealed all them to be post-mineralized. The first-stage dikes (DK1), based on composition, are subdivided into three types: DK1a, DK1b and DK1c.

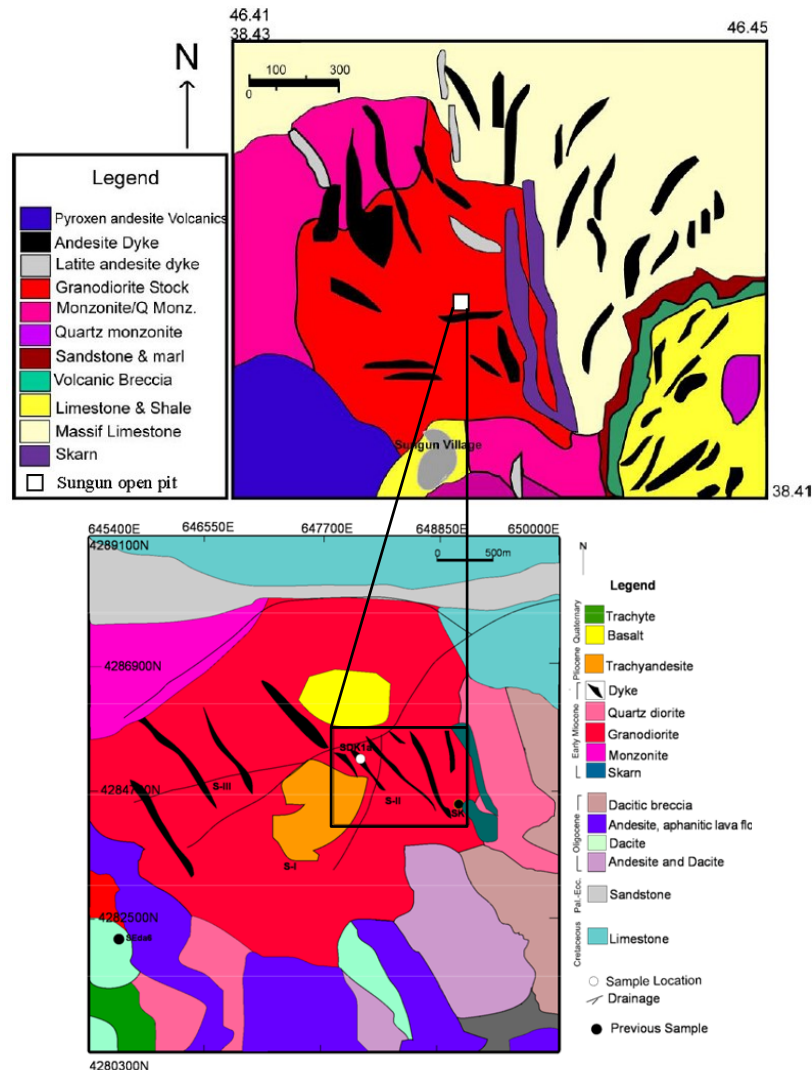


Fig 2. (Above) Simplified geological map of the Sungun area. The quadrangle marks the outline of the mine pit, shown in more detail in below with (modified after 426 NICICO 2006; Hassanpour et al. 2015). Samples (SDK1) from a dike in the present research, (Sk) and (SEda6) are pre published ages of the Sungun porphyry that have been discussed in compare with obtained age in the present research. (Below) Geological map of the Sungun deposit area, showing field relations among the various subtypes of Sungun intrusive rocks, and the outline of the mineralized zone. The porphyritic quartz monzonite is surrounding all of the other porphyritic plutons to the south and west, and Cretaceous limestones and associated skarns border the north and east. Andesite host rocks and andesite dikes are distributed through the north and western parts of the deposit (mainly outside the stock). Mineralized dikes intrude the quartz monzonite stock in the central part of the deposit. Main skarn-type alteration and mineralization occurs predominantly adjacent to the eastern margin of the stock (modified from Mehrpartou, 1993; Hezarkhani and Williams-Jones 1997).

Field studies showed that the DK1a and DK1b series occur as stocks in the SW part of the pit and intruded the Sungun porphyry intrusion. Based on NICICO, 2004, and Hamed, 2007, statistical studies of regional faults revealed four directions that coincide with directions of dikes exposed in the open pit mine. The NW-SE trending faults constitute the main faults of the area. Field evidence shows that the dikes selectively intruded into fractures, and they dip steeply toward the center of the intrusion (Hamed, 2007). Locally, the Sungun porphyries are covered by Late Tertiary-Quaternary volcanic rocks, ranging in composition from

andesite to latite (Emami and Babakhani 1991; 1996 Mehrpartou 1993; Calagari 1997; Hamed, 2007).

3. Mineralization and alteration in Sungun porphyry

Porphyry-style alteration-mineralization is well developed in the granodiorite porphyry and in the enclosing rocks. Potassic alteration-represented mainly by orthoclase and secondary biotite replacing original Fe-Mg silicates-dominates in the surface exposures, especially in the Pakhirschay river.

In the ore deposit, hydrothermal alteration is widespread, consisting of potassic alteration, silicification, kaolinization, sericitization, pyritization, chloritization, and carbonatization. The mineralization is closely related to the hydrothermal alteration. Potassic alteration, in the form of secondary K-feldspar and biotitization of mafic minerals and anhydrite fillings in the rocks, is dominant, with only local quartz-sericite overprinting, usually along late pyrite-bearing structures. Argillic alteration extends to a considerable depth, likely as a result of deeper penetration of meteoric waters along the easily dissolved faults and breccia matrix. Usually, deep weathering has left well-defined geochemical footprints of the deposits, with Cu and Mo acting as largely immobile elements, with their anomalies coincident with mineralization at depth. Hypogene ore is represented mostly by pyrite-chalcopyrite stockworks and disseminations; bornite is a rare constituent. Approximately 80% of the Cu–Mo mineralization is distributed in the granodiorite porphyry, with some of the mineralization hosted by the andesitic host rocks. Ore minerals are chalcopyrite and molybdenite, with minor amounts of bornite, galena, sphalerite, and magnetite. The gangue minerals are predominately quartz, feldspar, biotite, and sericite, with minor amounts of calcite and muscovite. Mineralization styles include disseminations and stockworks, exhibiting euhedral–subhedral and porphyry textures. Chalcopyrite and molybdenite in the granodiorite porphyry occur as granular disseminations and irregular veins associated with quartz veinlets. Molybdenite grains typically form as flakes, whereas chalcopyrite, pyrite, and bornite occur as disseminated grains and in fractures. Chalcopyrite and molybdenite quartz

stockworks are present in the porphyry rock. Abundant amounts of magnetite occur in association with Cu–Mo mineralization. The deepest drill holes at Sungun intersected homogeneous hypogene Cu grades (0.7% Cu) to more than 1,000m below surface. Skarn-type metasomatic alteration and mineralization occur along the contact between upper Cretaceous impure carbonates in the eastern and northern part of the Sungun open pit mine.

Based upon the petrography and texture, the associated alteration and mineralization episodes are seemingly continuous, and are recognized at Sungun skarn: (1) Early stage; (2) middle stage; and (3) late stage. The skarn-type ore in the Cretaceous carbonates consists of chalcopyrite and subordinate sphalerite, galena and magnetite.

4. Regional and local age relations

The Arasbaran magmatic belt extends from northwestern Iran, northward to Armenia (Fig 1). According to Sohrabi (2015), Hassanpour (2010) and Hassanpour et al. (2015), the Arasbaran magmatic belt lies to the south of the Lesser Caucasus, between the two northern and southern Azarbaijan sides, in particular. World-class porphyry systems like Sungun, Haftcheshmeh (economic reservoirs), Kighal, Niaz and Sheleboran (non-economic reservoirs) porphyry systems in Iran, in addition to two other porphyry systems in the country of Armenia, e.g. Kajeran and Dastakert porphyry ore deposits, are situated approximately with the same ages (20–22 Ma) in the Arasbaran-Armenia magmatic belt (Table 1).

Table1- Age data for Arasbaran magmatic belt, northwestern Iran

Deposit (rock Type)	Method	Mineral	Age	Reference
Sungun Dike (Dk1a)	U-Pb	Zircon	20.57±0.27	This study
Sungun (granodiorite Porphyry)	U-Pb	Zircon	20.69±0.37 Ma	Hassanpour et al. 2015
Sungun (Volcanic host rock)	U-Pb	Zircon	27.65±0.51 Ma	Hassanpour et al. 2015
Sungun (Potassic 1)	⁴⁰ Ar/ ³⁹ Ar	Biotite	20.20±0.24 Ma	Hassanpour et al. 2015
Sungun (Potassic 2)	⁴⁰ Ar/ ³⁹ Ar	Biotite	20.28±0.33 Ma	Hassanpour et al. 2015
Haftcheshmeh (granodiorite)	U-Pb	Zircon	19.46±0.39 Ma	Hassanpour et al. 2015
Haftcheshmeh (gabbrodiorite)	⁴⁰ Ar/ ³⁹ Ar	Biotite	27.47±0.17 Ma	Hassanpour et al. 2015
Kighal (granodiorite)	⁴⁰ Ar/ ³⁹ Ar	Biotite	20.10±1.8 Ma	Hassanpour et al. 2015
Niaz (granodiorite)	⁴⁰ Ar/ ³⁹ Ar	Biotite	22.14±0.13 Ma	Hassanpour et al. 2015
Kajeran	⁴⁰ Ar/ ³⁹ Ar		22 Ma	USGS
Dastakert	⁴⁰ Ar/ ³⁹ Ar		22 Ma	USGS

In the present paper, the point of view is the indication of the age difference between the Sungun porphyry and the first dike intrusion as a concentric magmatic activity. The older zircon age of the Sungun granodiorite/main porphyry implies that the large-scale, essentially Cu-dominated mineralization event, was largely coeval with the emplacement of the Sungun granodiorite.

5. Zircon U–Pb Methods and Sample description

A sample SDKA belongs to the earliest dike generation (Dk1) in the Sungun ore deposit. This sample—with porphyritic and microlitic textures—was taken from a dike near the Sungun porphyry in the western part of the Sungun skarn deposit (Fig 3). It was, furthermore, emplaced after the mineralization process of the Sungun porphyry as it cuts the mineralized main Sungun porphyry system. It is 2–10 meters wide and over 20 meters long, and has sharp contacts with the host porphyry. It trends in N310-350E and dips 80-90 toward NW (Fig 3). The dike varies from quartz diorite to quartz monzodiorite in composition and is yellowish gray to light greenish gray in color. Phenocrysts are quartz (coarse and rounded), altered biotite grains, muscovite and chlorite, and underwent weak to moderate phyllic and propylitic alterations (Fig 4 a,b). Although samples from a variety of dikes intrude the main Sungun porphyry system and were examined petrographically for the presence of magmatic zircon, only one dike sample from the Sungun area yielded an adequate number of good-quality zircon crystals. Fig 4 shows photomicrographs of the dike sample DK1a in both polarized and plane parallel transmitted light (Fig 4

A, B). SEM-CL images of dated zircons from the sample SDKA are shown in Fig 4 c, d.

In zircon U-Pb methodology: A SDKA sample of over 5 kilos was taken for U-Pb dating. After crushing, 10 zircon grains were separated from the sample SDK1a, followed by regular heavy liquid and paramagnetic separation. Prismatic bipyramidal zircon crystals (150 to 400 μm long) were hand-picked. Reflected and transmitted light photomicrographs and cathodoluminescence (CL) and scanning electron microscope images were prepared for all zircons. The CL images were used to determine the internal structures of the grains and to ensure that the 20 μm SHRIMP spot would analyze a single age component of the zircon. In situ U–Th–Pb analyses were performed on the SIMS, SHRIMP-II instrument at the Center of Isotopic Research (CIR) at the Karpinsky Russian Geological Research Institute, Saint Petersburg.

6. U–Pb dating results

Zircon U-Pb dating yielded a $^{206}\text{Pb}/^{238}\text{U}$ crystallization age of sample SDK1A (10 analyzed spots) from post-ore dike. These are listed in Table 2. The $^{206}\text{Pb}/^{238}\text{U}$ ages ($\pm 2 \sigma$) and representative U–Pb Tera–Wasserburg concordia plots are shown in Fig 4C and D. The zircons from sample SDK1a have euhedral zircons with subtle zoning, microcracks, and inclusions in inner and outer rim (Fig 4C, D). Figure 5 shows Tera–Wasserburg concordia plots of dated zircons from the sample SDKA. Based on these diagrams, the dike yielded $^{206}\text{Pb}/^{238}\text{U}$ ages of $20.51 \pm 0.27 \text{ Ma}$ and $20.57 \pm 0.27 \text{ Ma}$ (Fig 5b; 10 spots).

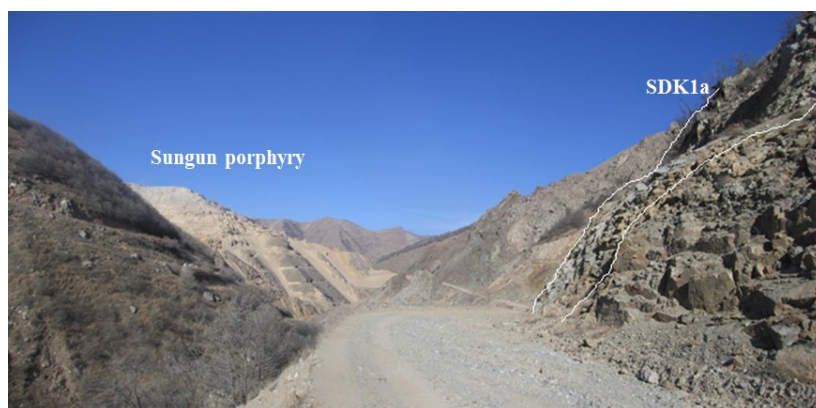


Fig 3. DK1a dike in eastern part of the Sungun mine (open pit) adjacent to the Sungun skarn deposit (looking north). Dated sample has been taken from this dike in this situation.

Table2. U-Pb data for zircon from sample SDKA from dike DK1 from the Sungun area. The data are listed with 2σ error ellipses; error bars and U-Pb ages are at ±2σ level.

Spot	% ²⁰⁶ Pb	ppm U	ppm Th	²³² Th/ ²³⁸ U	ppm ²⁰⁶ Pb ^s	-1 ²⁰⁶ Pb/ ²³⁸ U Age	-2 ²⁰⁶ Pb/ ²³⁸ U Age	-3 ²⁰⁶ Pb/ ²³⁸ U Age	Total ²³⁸ U/ ²⁰⁶ Pb ±%	Total ²⁰⁷ Pb/ ²⁰⁶ Pb ±%	-1 ²³⁸ U/ ²⁰⁶ Pb ^s ±%	-1 ²⁰⁷ Pb/ ²⁰⁶ Pb ^s ±%	-1 ²⁰⁷ Pb/ ²³⁵ U ±%	-1 ²⁰⁶ Pb/ ²³⁸ U ±%	err corr
SDKA.1.1	1.98	981	257	0.27	2.62	19.59 ±0.44	19.63 ±0.42	19.67 ±0.43	322.1 2	0.0606 9.1	328.6 2.2	0.0449 22	0.0188 22	0.003043 2.2	0.102
SDKA.2.1	2.05	1062	425	0.41	2.95	20.4 ±0.44	20.55 ±0.4	20.6 ±0.43	309 1.9	0.0573 5.7	315.4 2.2	0.0409 22	0.0179 22	0.00317 2.2	0.098
SDKA.3.1	0.78	1487	634	0.44	4.13	20.65 ±0.39	20.65 ±0.38	20.65 ±0.41	309.3 1.8	0.0525 4.6	311.7 1.9	0.0463 10	0.0205 11	0.003208 1.9	0.18
SDKA.4.1	0.62	1911	772	0.42	5.31	20.68 ±0.39	20.65 ±0.37	20.67 ±0.4	309.3 1.8	0.0527 2.6	311.2 1.9	0.0478 11	0.0212 11	0.003213 1.9	0.175
SDKA.5.1	1.2	1204	473	0.41	3.12	19.22 ±0.43	19.11 ±0.36	19.26 ±0.39	330.9 1.9	0.0602 3.6	334.9 2.2	0.0508 19	0.0209 19	0.002986 2.2	0.116
SDKA.6.1	0.79	1490	643	0.45	4.24	21.16 ±0.41	21.07 ±0.4	21.18 ±0.42	301.8 1.8	0.0562 7.8	304.2 1.9	0.0499 14	0.0226 14	0.003288 1.9	0.138
SDKA.7.1	0.75	1550	602	0.4	4.28	20.51 ±0.39	20.41 ±0.39	20.48 ±0.42	311.5 1.9	0.056 6.7	313.8 1.9	0.0502 10	0.022 10	0.003187 1.9	0.187
SDKA.8.1	0.82	2024	1089	0.56	5.68	20.83 ±0.39	20.82 ±0.38	20.94 ±0.42	306.4 1.8	0.0535 2.5	309 1.9	0.047 7.5	0.021 7.8	0.003237 1.9	0.24
SDKA.9.1	2.45	1045	407	0.4	3.05	21.37 ±0.56	21.39 ±0.44	21.47 ±0.46	293.8 1.9	0.0652 9.4	301.2 2.6	0.046 34	0.021 34	0.00332 2.6	0.077
SDKA.10.1	2.65	971	317	0.34	2.79	20.94 ±0.46	20.91 ±0.42	21.05 ±0.45	299.2 1.9	0.0684 6.4	307.4 2.2	0.0475 21	0.0213 21	0.003253 2.2	0.106

Errors are 1-sigma; Pb_s and Pb^{*} indicate the common and radiogenic portions, respectively.
 Error in Standard calibration was 0.66% (not included in above errors but required when comparing data from different mounts).
 (1) Common Pb corrected using measured ²⁰⁴Pb.
 (2) Common Pb corrected by assuming ²⁰⁶Pb/²³⁸U-²⁰⁷Pb/²³⁵U age-concordance
 (3) Common Pb corrected by assuming ²⁰⁶Pb/²³⁸U-²⁰⁸Pb/²³²Th age-concordance

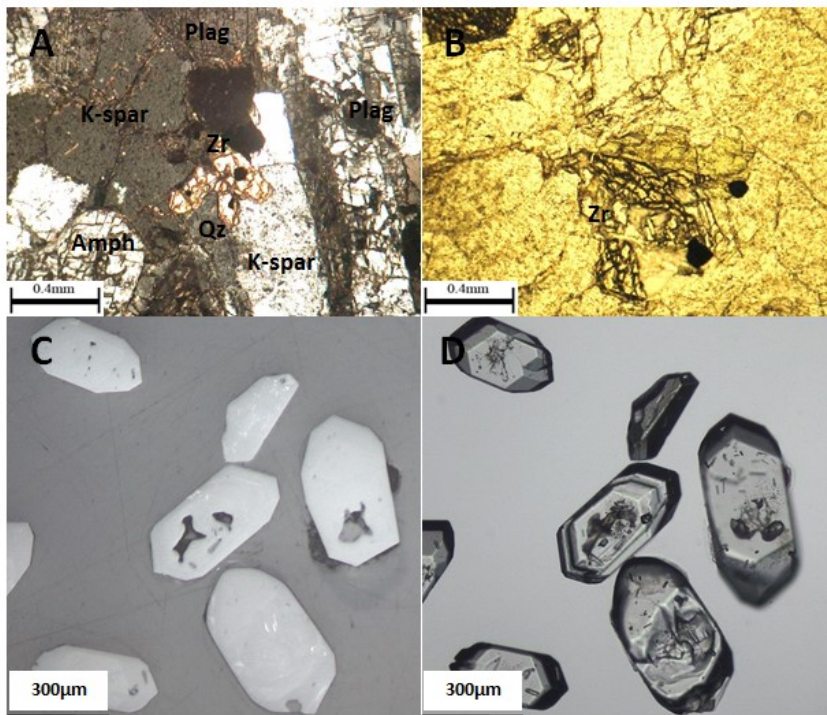


Fig 4. (a,b) Photomicrographs of the dike (DK1a) in polarized (a) and plane parallel (b) transmitted light; (c,d) scanning electron microscope images of dated zircons from the sample SDKA from dike DK1a.

7. Sr – Nd – Rb- Pb Isotopic Signatures

The Sr-Nd-Pb isotopic compositions of Sungun granodiorite and monzonite intrusives are used to delineate the nature of their source, and to determine the relatively proportion of mantle to crustal components in the generation of these voluminous granitoids. Two samples, one from granodiorite stock (Sungun granodiorite porphyry main stock) and another sample from the monzonitic later-intruded stock in the far distance of the open pit (but into the Sungun multiple intrusion system) were taken.

Isotopic composition measurements of two whole rock samples of granodiorite and monzonite sungun multicentral intrusions are shown in Table 3, and were determined on a Nu Instruments (Nu 021) multiple collector inductively coupled plasma mass spectrometer (MC-ICP- MS; Sr, Nd, Sm, Rb, Pb) at the Pacific Center for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia, Canada.

The Sr isotopic data of these suites are shown in a range of ⁸⁷Sr/⁸⁶Sr ratios from 0.704675 to 0.722785, in which the first sample is relatively the same, compared to other granitic rocks, and is quite similar to the Cenozoic

granitoids of the Andean orogenic belt (James 1989;

Hawkesworth et al. 1970; Hart 1988).

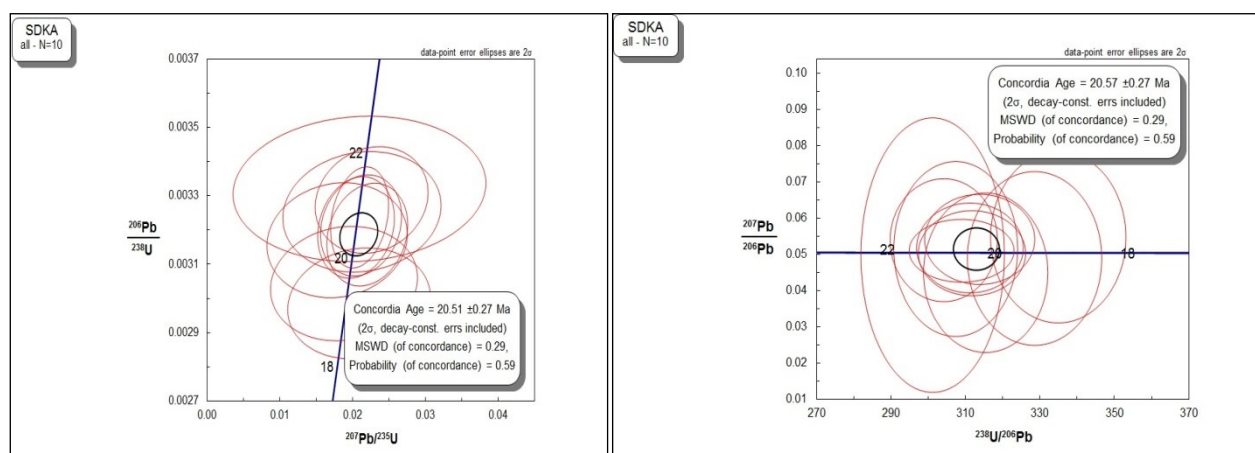


Fig 5. Tera–Wasserburg concordia plots; of dated zircons from the sample SDKA.

The second sample, however, seems to be contaminated because of the last intrusion sequence into the Sungun complex. As shown in Table 3, the lead isotope compositions of two samples of Sungun stock ranges from 18.67 to 18.86, from 15.65 to 15.66, and from 38.93 to 39.06 for the ratios of $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ respectively. In accordance with the Zartman tectonic pattern, this is the most commonly used lead isotope tracer diagram (Zartman and Doe 1981; Zartman and Haines 1988), the projecting points are mainly located the upper crust to the orogeny zone (Fig 6a, b) (Zartman and Doe 1981). The whole rock lead is relatively concentrated in the lead isotope tectonic pattern and projects onto the island arc zone, which is away from the upper crust, lower crust, and oceanic island volcanic zones. Moreover, its distant origin in the upper and lower crusts may be related to the subduction arc material or oceanic crust. Figure 6C and D indicate the source of two samples from the upper crust to the orogeny zone. The results of lead isotope of two intrusion rocks of Sungun stocks compare with Nd, Sr, Pb isotopic data of granitoid rocks of Chile's Andean region (James 1989; Hawkesworth et al. 1970; Hart 1988; Fig 6 e, f). Subsequently, it suggests that this

stock has originated from a subduction environment similar to the Chilean region and it can have the same source or origin with the Sungun area.

Based $^{87}\text{Sr}/^{86}\text{Sr}$ values of depleted mantle, lower crust and upper crust ($^{87}\text{Sr}/^{86}\text{Sr} \sim 0.703, 0.708, 0.740$ respectively; DE Paolo et al. 1991), so it can be recommended that the Sungun magmas were almost produced by the melting of mantle-derived materials. These granitoids, moreover, have a distinctly low range of Rb/Sr (0.67497 to 0.67415 values) within SiO_2 content, ranging from 61 to ~65 percent (Table 3), which are based on Blevin and Chappell (1995) and consistent with their derivation from mantle materials and deficient contribution of crustal materials. The isotope ratios of Sr, Nd and Pb of the volcanic rocks on the Barroso and Arequipa Volcanoes in Fig 6e and f exemplify the extensive crustal contamination of mantle derived magmas in the Central Volcanic Zone of the Andes. The data fields of the lavas on these volcanoes are located far from the DMM component in the fourth quadrant of the Sr-Nd isotope mixing diagram and beyond the locations of EM1 and EM2.

Table3. Sr, Rb and Sm-Nd isotopic data of intrusions from the Sungun

Rock Type	SiO_2	Sr	Nd	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{147}\text{Sm}/^{143}\text{Nd}$	$^{145}\text{Nd}/^{144}\text{Nd}$	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
Granodiorite	64.38	681	1.468	0.704675	0.512753	0.29235	0.348406	0.67497	18.86122	15.65183	38.93809
Monzonite	61.29	639	1.582	0.722785	0.512139	0.29227	0.348404	0.67415	18.67337	15.6696	39.06293

Therefore, the isotope ratios of Sr and Nd of the Barroso and Arequipa lavas are not attributable to the metasomatic alteration of the mantle wedge alone, but also require inputs of Sr and Nd from the rocks of the continental crust. The data in Fig 6e also emphasize the difference between the lavas of the Central Volcanic Zone and those of the Northern and Southern Volcanic Zones. The isotope ratios of Sr and Nd of the lavas of Ecuador (Northern Volcanic Zone) in Fig 6e differ markedly from those of the Peruvian lavas and are consistent with their derivation from the mantle wedge, with minimal contamination by Sr and Nd of the continental crust. The lavas of Patagonia and southern Chile in the Southern Volcanic Zone of the Andes have a wide range of Sr and Nd isotope ratios, implying that the extent of crustal contamination of the magmas ranged from insignificant in Patagonia to quite extensive in southern Chile (Hawkeswarth et al. 1979b; James 1982). The Sungun stock shows a datume similar to Patagonia (SVZ). The isotope ratios of Sr and Pb in the lavas on the Arequipa and Barroso Volcanoes in southern Peru define a mixing array in Fig 6f, indicating that the crustal component had a lower $^{206}\text{Pb}/^{204}\text{Pb}$ ratio than the mantle component (James 1982). Therefore, all the isotopic data considered here consistently demonstrates that the magmas in the study area are similar to the Andes-assimilated significant amounts of granitoids of the continental crust. The ore deposits of Mesozoic to Early Tertiary age in the coastal area of the central Andes rocks of the high Andes as well as the Sungun stock rocks also contain mixtures of mantle-derived and crustal Pb (Macfarlane et al. 1990).

8. Discussion

The 20.51 ± 0.27 Ma zircon age for the dike SDK1a shows that it intruded and crystallized shortly after the Sungun porphyry for which Hassanpour et al. (2015) obtained a 20.69 ± 0.37 and Aghazadeh et al. (2015) obtained an age of 21 ± 0.15 Ma U-Pb zircon ages. Zircon ages for dikes in generally named early and late stages obtained by Aghazadeh et al. (2015) are 19.78 and 19.51 Ma (in Persian reference) and are not useful for our discussion because of different analyses of laboratory data and/or probable error in sampling process. All our results and data correspond to the accuracy of each other.

In this research, both zircon ages are indistinguishable, as they overlap at 2σ level within analytical uncertainty, indicating that the succession of magma injections at Sungun took place within a short period of about 0.12 Ma that falls within the analytical uncertainty of the SHRIMP U-Pb dating method. The U-Pb data prove an early Miocene crystallization age and refute an Oligocene-Miocene age for intrusive and subvolcanic rocks proposed in previous studies (Hassanpour et al. 2015; Aghazadeh et al. 2015). Thus, a major phase of magmatism occurred in the early Miocene, but it should

be noted that the new age does not delimit the complete succession of magmatic activity in the Sungun mine area because of several concentric intrusions.

The published 20.69 ± 0.37 Ma zircon age for the mineralized granodiorite porphyry at Sungun (Hassanpour et al. 2015) approved the emplacement age of the porphyry intrusion. Its crystallization age is significantly younger than the 27.7 ± 0.5 Ma U-Pb zircon crystallization age of the andesitic surrounding rock (Hassanpour et al. 2015), confirming that the latter represents a much older magmatic episode.

These ages offer older age limits for the porphyry system and related later intrusive phases, and further clarified the true age of volcanism and plutonism in northwestern Iran. Previous studies suggested that this part of Iran belongs to the volcano-plutonic Urmieh-Dokhtar belt (e.g. Hezarkhani 1997; Mehrpartou 1993; 235 Calagari 1997), but Hassanpour (2010) and Sohrabi (2015) showed that the Arasbaran copper belt is geodynamically different from Urmieh-Dokhtar magmatic belt. The magmatic rocks at Sungun represent a stage of magmatic activity that is older than that of the Sarcheshmeh porphyry copper deposit, where granodiorite stocks and sills related to the main stock have U-Pb zircon ages between 13.6 ± 0.1 Ma and 10.9 ± 0.4 Ma (Aghazadeh et al. 2015; McInnes et al. 2005). In addition, 12.5 Ma U-Pb zircon ages were reported for the Meiduk porphyry copper deposit (McInnes et al. 2005), also indicating a mid- to late-Miocene age for porphyry mineralization in SE Iran, compared to early Miocene ages for NW Iran. The intrusion of the 20.69 Ma main Sungun porphyry (exposed in the open pit) considerably predates the andesitic volcanism, but overlaps in time with a 20.5 Ma dike emplacement determined for a sample from this mine. Therefore, at least in the Sungun porphyry, Cu-Mo mineralization occurred during the emplacement of the main porphyry and dike system. Ore formation was probably initiated during, or immediately following, intrusion of the granodiorite porphyry (main mineralized porphyry stock) and probably completed at least up to the time of emplacement of the DK1a dike. Despite some uncertainties, it is clear that Cu-Mo mineralization overlapped with the multiple phase of late porphyritic dikes and that the ore zones developed between intrusion of the Sungun porphyry body (mineralized) and the first generation dike system (non mineralized) "120,000 y".

Our isotopic data consistently demonstrates that the magmas in the Sungun region are similar to the Andes-assimilated significant amounts of granitoids of the continental crust. The Sungun ore deposit like Mesozoic to Early Tertiary age in the coastal area of the central Andes rocks of the high Andes contain mixtures of mantle-derived and crustal Pb (Macfarlane et al. 1990).

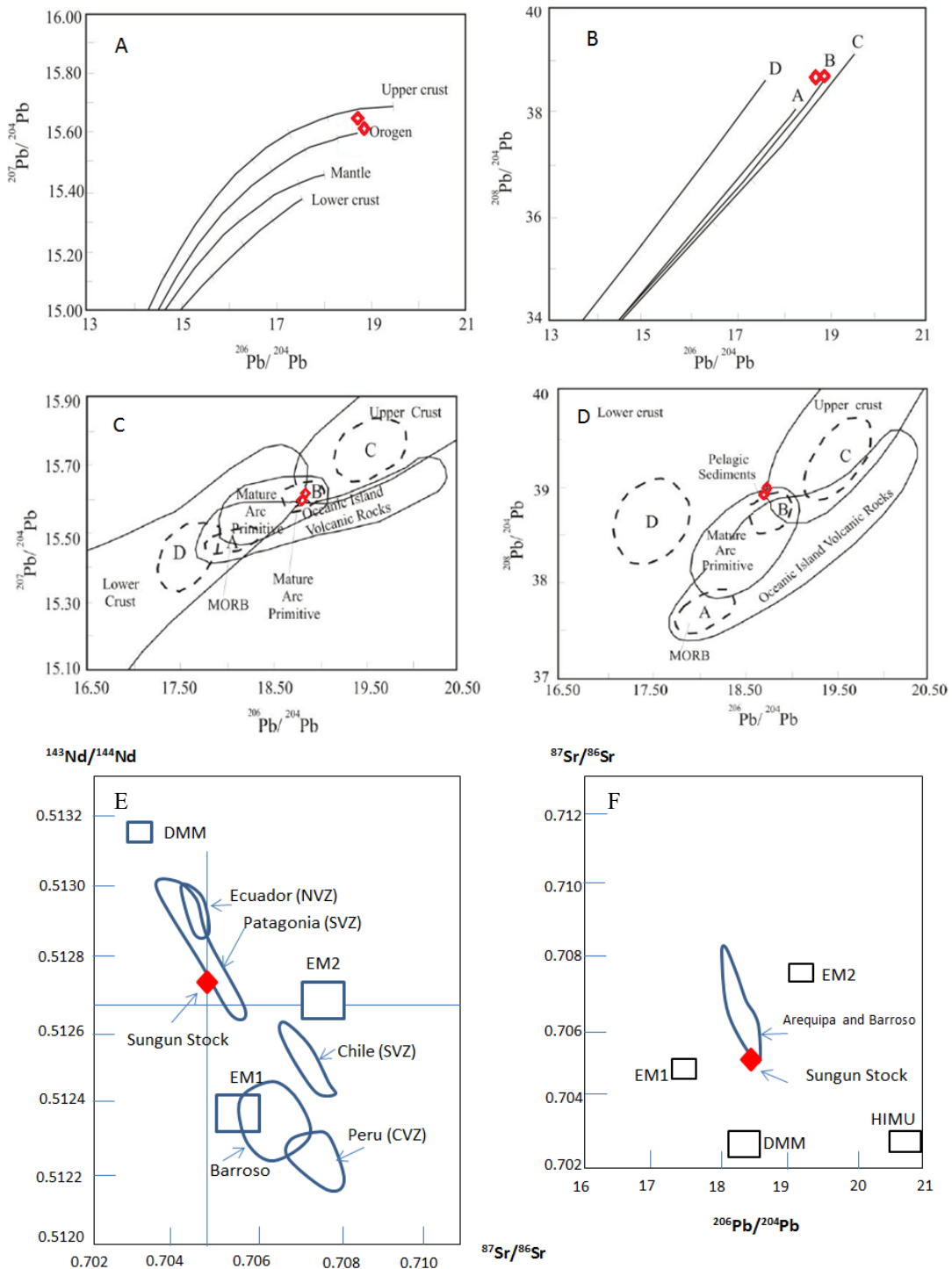


Fig 6. (a) $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ diagram of granitoid stocks from the Sungun (Zartman and Doe 1981), (b) $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ diagram of mafic stocks from the Sungun, Lead-isotope evolution curves generated by the 8 plumb tectonics model for the mantle (A), orogene (B), upper crust contributed to the orogene (C), and lower crust contributed to the orogene (Zartman and Doe 1981). (c) Diagrams for discriminating tectonic settings (Zartman and Doe 1981), (d) $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ diagram, (e) Isotope ratios of Sr and Nd of Sungun samples in compare to late Tertiary rocks in Peru in NVZ and CVZ. The isotopic data reveal the full range of petrogenesis from magma formation in the mantle wedge (modified after: James 1982; Hawkesworth et al. 1979; Hart 1988), (f) Isotope ratios of Sr and Pb of Sungun magma in compare to samples from southern Peru (Source: Cobbing et al. 1977; Shackelton et al. 1979; Tilton and Barreiro 1980; Hart 1988).

9. Conclusions

The Sungun intrusive complex crystallized at 20.7 ± 0.6 Ma during early Miocene and significantly post-dates its andesitic host rocks by about 7 Ma. Emplacement of porphyritic dike system took place within NW-SE

trending faults that splay from the adjacent N-S trending, sinistral strike-slip Sungun fault zone at the onset of transpression in a supra-subduction magmatic arc. Published U-Pb data for the host rocks of the Sungun copper porphyry deposit and later dikes provide

precise age constraints for the late Miocene porphyry-type mineralization episode in the Arasbaran magmatic belt of northwestern Iran. Based on radiogenic isotopes, the Sungun main granodioritic stock also have a range of $^{143}\text{Nd}/^{144}\text{Nd}$ and low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, and $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$ values for this body that are essentially explained largely by the contribution of the modified subcontinental mantle wedge in the petrogenesis of the region magma. Trending is to be so tightly constrained in composition, which is deliberated to have been derived from a limited range of source materials.

In these rocks for which the Sr-Nd-Pb isotopic data and the other chemical features suggest a little crustal contamination, we suggest a discontinuous magma generation and direct ascending model rather than long-lasting lower crustal storage-contamination models like the MASH (melt, assimilation, storage, and homogenization) model. It is indicated that the granodiorite and monzonitic intrusions of Sungun are essentially generated by partial melting of the mantle wedge above subducting oceanic lithosphere. The Sungun stocks are intruded as the latest subduction related magmatic suite in the late stage of AMZ development. Radioisotope features indicate a substantial contribution of mantle material in the generation of thick continental crust in the Sungun area and provide strong evidence for a continental crust growth, in AMZ at the Mesozoic-Cenozoic time interval.

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