Metallogeny of Turkey
A Diverse Collisional and Post-Collisional Environment for Mineral Deposits

SUMMARY
Turkish Tethyan collage is fragmented suite of microcontinents resulted from subsequent events in response to collision between Eurasian and Afro-Arabian plates during Late Cretaceous to Late Miocene time period; and closure of the NeoTethys ocean and a marginal oceanic basin, the İzmir - Ankara - Erzincan (northerly ocean). The collision has taken place along the Pontides, Bitlis - Zagros suture, and active Aegean subductions. Turkish Tethyan collage is a highly fertile metallogenic environment with abundant volcanogenic massive sulfide, skarn, porphyry Cu and epithermal Au-Ag deposits in the entire TEMB and Turkey, clustering in narrow arc segments, and post to late orogenic extensional settings. The available data shows that these deposits are associated both with Late Cretaceous magmatic arc (Pontides and Bitlis - Zagros subductions), Late Paleocene - Early Eocene extension-driven post-collisional settings (Pontides, Tavsanli zone, central Anatolian Crystalline Complex and southeastern Anatolian Orogenic belt) after continental collision, and Middle to Late Eocene - Early Oligocene to Late Miocene extensional settings within overriding plate in a Aegean subduction zone (Bİga peninsula, Western Anatolian Extentional province).

The gold deposits vary from gold-only subtype to by-product gold types. These include porphyry Au deposits (e.g. Kişladağ - Uşak) and epithermal Au-Ag and base metal deposits (e.g. Ovacık - İzmir, Mastra - Gümüşhane, Ağıdağı - Çanakale, Efemçukuru - İzmir, Küçükder Dolu - Balikesir, Öksüt - Kayseri) and Cu-Au deposits such as porphyry Cu-Au (e.g., Çöpler - Erzincan, Halilağa - Çanakale, AS - Afyon), proximal copper-gold skarn (e.g. Ayazmant - Çanakale, Evcilir - Çanakale) and distal silver-base metal (e.g. Korus - Çanakale, Balıa - Balikesir, Çataltepe - Çanakkale) deposits. The lead-zinc deposits are mainly VMS-type (mainly Kuroko-type) in the Pontides; distal to manto-type mesothermal veins in the western Anatolian extensional province (WAEP), skarn type in central Anatolian crystalline complex (CACC), and carbonate-hosted or Mississipil Valley type (MVT) in the central to eastern Taurides. The copper deposits are mainly of porphyry type in Pontides with close association with molybdenum; Cyprus to Beshi-type in the southeastern Anatolia; skarn type in the WAEP. Apart from gold, copper, lead and zinc deposits, Turkey is also host to podiform chromite deposits which are widely associated with supra-subduction zone ophiolites derived from the southerly and northerly NeoTethys oceans or marginal oceanic basins (Vardar, or İzmir - Ankara - Erzincan Ocean) formed during the closure of NeoTethys. Although whole rock and mineral ages scatter 112 and 9 Ma, some deposits in this belt formed during short-lived magmatic events related to tectonic processes such as subduction, rollback / hinge retreat, continental collision, lithosphere delamination or tears in the subducting slab as the Arabian and African plates began to collide with the Eurasian plate during the opening, final closure and terminal suturing of the NeoTethys Ocean between Late Cretaceous to Quaternary period. There are also some known deposits that are potentially of Carlin-type, detachment fault-related gold-type, and gold in carbonate replacement and Mn-deposits, which are being exploration targets.

The above mentioned deposits are the direct consequences of three subductions and resultant collisional - post collisional events that took place at Pontides between 112 - 75 Ma, 52 - 39 Ma; at CACC between 79 - 73 Ma and 11 - 9 Ma; at SEAOB between 83 - 79 Ma to 54 - 44 Ma, and at WAEP between 39 - 11 Ma. This review permits the construction of the temporal and spatial framework of magmatism and associated mineralization in the evolving NeoTethyan orogen, and shed light into major episode(s) and tectonic setting(s) of productive (fertile) magmatism in a transition from subduction related to post-collisional, and to late-orogenic events in Turkey.

INTRODUCTION
Turkey is one of the few countries that possess poly-metallic resource base, lying at the junction of the African, Eurasian and Arabian plates that resulted in repeated episodes of orogeny, magmatism and arc formation (Fig.1). This has resulted in a geologically active environment, making it possible for magma and hot fluids to well up from the mantle that have created innumerable mineral deposits. The Mesozoic to Cenozoic Alpine - Himalayan orogenic belt (Tethyan collage) stretching from Spain, to the east across Europe into Turkey, Iran, and southeast Afghanista, Pakistan and the Himalayas, is an extremely complex geologic terrane caught between colliding continents (Perello et al., 2008). This belt is also known as the Tethyan - Eurasian metallogenic belt (TEMB; Jankovic and Petrascheck 1987). Turkey, as a part of this belt was formed since the Carboniferous, as the Arabian and African plates began to collide with the Eurasian plate during the opening, final closure and terminal suturing of the Tethys Ocean between Late Cretaceous to Quaternary period. In the Turkish part of TEMB, these complex environments are host to a wide spectrum of ore deposits including volcanogenic massive sulfide, skarn, porphyry, epithermal and IOCG. These deposits form several belts that stretch across Balkans to Turkey and continue into Georgia, Armenia to the north and Iran to the southeast (Figure 1); principally in the Pontides, central-eastern to southeastern Anatolia, and western Anatolia. The geodynamic setting of the Tethyan
collage in Turkey is reasonably well known. A similar understanding of the metallogenic evolution, is also well constrained (Kuşcu et al., 2013a; 2013b; Boztuğ et al. 2003; Yiğit, 2005; 2009; Kaymakçı and Kuşcu 2007). Besides, the spatial and some geological characteristics features of Late Cretaceous and Tertiary ore deposits of the Turkish Tethyan collage are also well documented (Yiğit, 2009), as is the relationships between regional tectonics, magmatism and ore formation (Kuşcu et al., 2010; 2013a; 2013b; Boztuğ et al. 2003; Yiğit, 2005; Kuşcu 2005). The common association of Cu-Au deposits worldwide with subduction-related calc-alkaline magmas in continental arcs are quite clear, and well documented; Andes, North American Cordillera, Papua New Guinea, and China (e.g., Sillitoe 1972; Richards et al. 2001). Some deposits formed during extensional regimes whereas others occurred towards the end of collisional events. The recent works showed the existence of a suite of porphyry Cu deposits in collisional zones (Hou et al., 20011; Hou and Cook, 2009) and intracontinental settings. Turkey, as being the part of an orogeny at the expense of colliding Eurasian, Arabian and African plates, forms a belt where subduction-related and post-collision related mineral deposits are present. This review summarizes the main metallogenic points of Turkey in relation to Tethyan evolution, and benefited much from the earlier compilations.

NEOTETHYAN GEOLOGIC EVOLUTION OF TURKEY

The geologic - geodynamic evolution of Turkey is related to several subduction and collision events since the Precambrian, and is largely known as PaleoTethyan and NeoTethyan evolution. The works on the NeoTethyan evolution of Turkey enabled the recognition of three subductional - collisional events (Okay and Tüysüz, 1999; Göncüoğlu et al., 2000; Stampfl and Borel, 2002; Bozkurt and Mittwede, 2001). These events are due to; (1) closure of the northerly ocean, IAE ocean (collision between TAB and SM (Eurasian plate, sensu lato) in the north between ca. 110 - 39 Ma (2) closure

Figure 1. (a) Digital elevation map (DEM) of western Tethys illustrating the present configuration of major plates in Turkey, (b) Tectonic map of western Tethys showing main tectonic units, mineral deposits (From Kuşcu et al. 2013b)
of the southerly ocean, NeoTethys (collision between Arabian plate and TAB) to the south between 83 - 44 Ma (Kuşçu et al., 2013a), and (3) closure of the Mediterranean Sea, the remaining NeoTethys ocean (collision between TAB and African plate) to the west between 28 Ma to recent. These events were resulted in accretion of continents, amalgamation of microcontinental fragments and ophiolitic thrust slices. The first one is related to northward subduction of IAE oceanic lithosphere beneath the Eurasian continental margin, which was later metamorphosed to form the metamorphic basement in the Pontides (Fig. 1b; Fig. 2), and formed a magmatic arc in the Pontides. The second one is related to northward subduction of the Neotethys beneath TAB, and formed Baskil - Zagros subduction in the SEAOB. The third one is related to northeastward subduction of the Ionian part of the Eastern Mediterranean Sea and formed Helicen - Aegean subduction in the western Anatolia. During the first subduction event, most of the oceanic lithosphere belonging to IAE ocean was consumed firstly by intra-oceanic subduction that formed intra-oceanic OIB-type seamounts with (supra-subduction zone ophiolites, SSZ) at ca. 117 Ma and active margin along the Pontide subduction (Kaymakci et al., 2009). The SSZ ophiolites, widely exposed along the IAESZ (Fig. 1b; Fig. 2), have a geochemical composition intermediate between MORB and arc series, and were emplaced in deep marine slow-spreading basins. The volcanogenic massive sulfide deposits consisting of variety of Pb-Zn-Cu ore bodies within dacitic - rhyodacitic series within the Pontide arc. Following the subduction, the Pontides collided with TAB, and ophiolites were obducted onto the TAB (Okay and Tüysüz, 1999; Göncüoğlu et al., 2000; Bozkurt and Mittwede, 2001; Stampfli and Borrel, 2002; Rolland et al., 2009; 2011; Kuşçu et al., 2011 and 2013a) into the metamorphic massifs and obducted ophiolites. This emplacement also resulted in regional HP metamorphism of the metamorphic soles below ophiolites, and TAB. The Strandja Massif (Menderes Massif and Central Anatolian Crystalline Complex (Sengor et al. 1984; Göncüoğlu et al., 2000) are examples of such metamorphic massifs (Fig. 2) formed by the ophiolitic nappes in Turkey. Rolland et al. (2009) suggested that the continental collision between SM and TAB and southward emplacement of the ophiolites and OIB sequence onto the TAB took place at ca. 85 - 80 Ma.

After the final suturing of the Pontides and TAB, the continental lithosphere was subducted underneath the Pontides. This was followed by subsequent post-collision related extensional tectonics. This gave rise to (1) bimodal, shallow-seated and extensional magmatic complexes emplaced into the metamorphic basements during ca. (57) 48 to 42 Ma (Arslan and Aslan, 2005; Boztuğ et al., 2007; Karslı et al., 2010; Eyuboğlu et al., 2011; Karşılı et al., 2010).

Figure 2. Simplified geological map of Turkey showing the main magmatic rocks (from Kuşçu et al., 2013b)
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The available data is favor of a slab break-off or slab-roll back process in the generation of these magmatic rocks in Pontides ( Genç and Yılmaz, 1997; Arslan and Aslan, 2006; Kaygusuz et al., 2011) However, according to some authors, the break-off or roll back process is unlikely, and these magmatic rocks were formed in a post-collisional environment due to delamination (Eyuboğlu et al., 2011)

The second subduction initiates at the southern part of the TAB along Bitlis - Zagros subduction while northern margin docks into the Northern subduction zone. This temporal relationship is interpreted to be a subduction jump from the north to the south of the TAB at ca. 85 - 80 Ma (Rolland et al., 2011). To the south, the main events separating the TAB from the Arabian plate took place between ca. 83 - 79 Ma witnessed northward subduction of Neotethys (the second subduction event) below the TAB forming the Bitlis - Zagros subduction event (e.g., Agard et al., 2005; Robertson et al., 2005; Rolland et al., 2011; Kuşcu et al., 2013a and references therein). During the second subduction event, most of the oceanic lithosphere belonging to southerly ocean, NeoTethys between Arabian plate and TAB was consumed firstly by intra-oceanic subduction that also resulted in supra-subduction zone (SSZ) ophiolites at c. 90 - 95. These SSZ ophiolites were then emplaced over the southern margin of the TAB (Fig. 1b) forming the Malatya - Keinan metamorphics (Robertson et al., 2005; Kuşcu et al., 2013a). This was followed by the closure of the NeoTethys oceanic basin that resulted in an active margin along the Bitlis - Zagros subduction between 83 - 79 Ma (Kuşcu et al., 2013a). The subduction resulted in voluminous calc-alkaline intrusive magmatism emplaced into Malatya - Keinan and Bitlis - Pötürge metamorphics (Fig. 2). This short-lived subduction was terminated due to collision between Arabian plate and TAB, and is marked by the emplacement of the ophiolitic nappes over the Bitlis - Pötürge metamorphic massifs within the SEAOB. The high temperature metamorphism of the Bitlis - Puturge dated as ca. 74 - 71 Ma (Göncüoğlu and Turhan, 1984; Rolland et al., 2011). This metamorphic age was interpreted as the timing of continental lithospheric subduction (underthrusting) underneath TAB before the final suturing of Arabian and Eurasian plates (Rolland et al., 2011). Following the underthrusting of the metamorphics underneath TAB, the whole region experienced a post-collisional extension due to decrease in the convergence rate between Arabian and Eurasian plates (Savostin et al., 1986; Kuşcu et al., 2013a) and delamination or roll-back of the subducted slab between ca. 77 to 54 Ma (Kuşcu et al., 2013a; Rolland et al., 2011) that exhumed the metamorphic basement, unroofed previously obducted ophiolites, and filled basins with Maastrichtian to Paleocene subaerial and submarine sedimentary rocks. Initial extension coincided with emplacement of calc-alkaline to alkaline magmatism ranging from ca. 77 to 73 Ma in central and southeastern Anatolia (Kuşcu et al., 2011), then by alkaline magmatism peaking at 74 - 71 Ma (Kuşcu et al., 2013a) mostly at eastern and southeastern Anatolia. The subsequent magmatism took place in Pontides, Tavsanlı zone and SEAOB took place between early to Middle Eocene (~52 and 44 Ma, peaking at 48 Ma; Kuşcu et
al., 2013a). Several works that favored an arc origin for the Eocene magmatic rocks (Yiğitbaş and Yılmaz, 1996; Richards, 2003), and slab break-off origin (Onal et al., 2005), appears to be inconsistent with the available geologic evidence. However, the commonplace of Eocene igneous rocks (volcanic and volcaniclastic rocks) coexisting with or emplaced into fault-bounded sedimentary basins are favor of extensional events (Kuşçu et al., 2011; 2013a). The final continental collision and suturing of Arabia with the ATB and metamorphosed counterparts of eastern Taurides in the middle Miocene was followed by a slab-steepening and break-off beneath the ATB (Sengor et al. 2003).

The Late Eocene - Oligocene compression is very widespread and extends from eastern Turkey to Aegean region and further west into Greece. This collision resulted in extrusion of TAB into Greece, and Hellenic - Aegean subduction zone (third subduction event). The Aegean subduction peaking at about 42 - 26 Ma (Kuşçu, 2009; Kuşçu et al., 2013b) produced isolated continental arc magmatism mainly in the western, northwestern Turkey. The field observations supported by geochronologic and geochemical data (Kuşçu, 2009) on magmatic events suggested that that Aegean subduction is accompanied by a lithospheric extension, exhumation, core-complex development, subduction and extension-related magmatism and large-scale, probably gravitational gliding of the Lycian Nappes system approximately between 24 - 23 to Plio-Quaternary (Aldanmaz et al., 2000; Doglioni et al., 2002; Kuşçu, 2009; van Hinsbergen et al., 2010; Kuşçu et al., 2013b). The recent lines of evidence argue that there is no single mechanism and time period responsible for the extension in WAEP instead roll-back, slab break-off and differential decoupling and internal deformation - disruption processes appear to worked together through time starting from Middle Eocene to Plio-Quaternary. The central and eastern Anatolia, however, experienced voluminous magmatism starting from Mid-Miocene to Quaternary that produced several phases of calc-alkaline and alkaline magmatism within previously metamorphosed sedimentary - volcanosedimentary sequences. These are interpreted to be related to transtensional regime or slab break off event after the final suturing of Arabian plate and Anatolides.

**METALLOGENY OF TURKEY**

As a part of the TEBM, Turkey has many characteristics similar to surrounding countries and host many volcanogenic massive sulfide, porphyry-type, skarn and hydrothermal and magmatic deposits. These deposits occur within regional belts that could be traced across the neighboring countries (The opening of NeoTethys and resultant passive margin evolution ocean caused subsidence of the continental margin, which created extensive platform shelf areas where carbonate-hosted lead/zinc/silver deposits such as those widely discovered in the central and eastern Taurides formed during the Lower - mid Cretaceous. Although the magmatic and metallogenic processes were dominant in the Jurassic - Miocene time interval, the principal mineralization types have been formed during different metallogenic epochs starting from Late Cretaceous to Late Mioc. - Pliocene times. The earliest significant mineralization events of the Neotethys in Turkey occurred during late Jurassic to Early Cretaceous when an intra-oceanic subduction (supra subduction) formed due to initial closure of the northerly ocean (Vardar - Izmir - Ankara ocean), and an incipient roll-back. This event accompanied also by formation of the supra-subduction zone ophiolites, is the first metallogenic epoch (110 - 90 Ma) associated with magmatic segregation type podiform chromite deposits. The subduction in the pontides, then, has been achieved through in two successive stages; an early phase producing island-arc type volcanic - volcanoclastic sequences mainly during Late Jurassic to Early Cretaceous, and a later phase producing arc-type intrusive magmatism during Late Cretaceous. The early phase which could also be termed as the second metallogenic epoch was responsible for the formation of volcanogenic massive sulfide deposits in marine basins along with the Eastern Europe and Iran. These include major deposits such as Çayeli and Murgul in the Eastern Pontides. The later phase, Late Cretaceous (~85 - 77.5 Ma, 2009) subduction events that created arc magmatism (diorite to granitic) and associated Cu-Mo porphyry mineralization at the NW, NE (Pontide subduction) and SE (Bitlis - Zagros subduction) in Turkey corresponds to the third metallogenic epoch, an epoch during which porphyry systems were predominant. The third metallogenic epoch at the expense of Pontide subduction produced porphyry style (Demirköy and Dereköy) and skarn (Armutveren and Şüküruşa) mineralization close to Bulgarian border at Kırklareli and Edirne, and some sub-economic Cu-Mo porphyries like Balcılı, Börekli and Pohrenk, Ulutaş and Güzelyayla at the eastern Pontides. Apart from these, Late Cretaceous porphyry systems are scarce in the Pontides. The same time period during which southerly ocean was consumed along the Zagros - Bitlis subduction, and associated with volcanic-plutonic magmatism is more favorable in producing porphyry systems hosted by granodiorite to tonalite - dacitic rocks exposed as an arcuate belt from Kahramanmaraş, Bitlis, Elazığ and south of Tunceli. The postcollisional extensional events after the main continental collision (collision of Eurasian plate with Anatolides at the north, Vardar - İzmir - Ankara - Erzincan suture; and collision of Arabian plate with Anatolides at the south, Bitlis - Zagros suture) generated voluminous magmatism and associated mineralization as the fourth metallogenic epoch. This also corresponds to a Mesozoic - Tertiary boundary (Uppermost Cretaceous to Lower-Mid Paleocene during which a major crustal extension is predominant throughout Turkey. This epoch has no associated mineralization within the Pontides, but is extensive within the central Anatolia and SEAOB in the metamorphic terranes intruded by post-collisional (late orogenic) I- to H-type calc-alkaline granitoids and I-type alkaline volcano-plutonic associations. During this epoch, as an early phase (74 - 73 Ma) calc-alkaline magmatism (monzo-diorite, granodiorite to Q-diorite) was formed by a roll-back-driven mechanism or exhumation of metamorphics, and produced IOCG
Aegean subduction, that produced plates have been accommodated by during which the convergence for the metallogenic history of Turkey Eocene to late Oligocene - Miocene. post-collisional volcano-plutonic skarns are limited and associated with high sulfidation characteristics. The systems with low sulfidation and to epithermal (to mesothermal?) systems. These are mostly skarn, porphyry Eocene to Pliocene are recorded. and extrusive magmatism from region where a continuous intrusive occurrence/mineralization within deposits such as Cu-F-Mo porphyries (Keban, Yeşilyurt - Malata), Fe- and Pb-Zn skarns (Durmuşlu, Keban) and IOCG deposits (Hansaçelebi, Karakuz) as a late phase (74 - 69Ma, Kuşçu et al., 2011) at eastern Anatolia and northern parts of the SEAOB. The final suturing of the Afro-Arabian plates with the Eurasian plate, and continued N-S convergence caused either initial slab rupture and/or a STEP faulting at the overriding plate within the SEAOB (Kuşçu et al., 2010a), slab break-off within the Pontides, and western Anatolia. This was resulted in partial melting and shallow seated bimodal volcanic-plutonic complexes with a striking adakite-like geochemical fingerprinting formed during Early - Middle Eocene (~57 - 39Ma, Kuşçu, 2009) at Pontides, SEAOB, CACC and western Anatolia. This is accepted as the fifth metallogenic epoch during which abundant economic porphyry Cu-Au, Au at SEAOB (Çöpler, Kabataş, İllic) and Mastra, Bahçeçevik, Bıçak, Berta and Konak at Pontides; Fe-, Fe-Cu skarns at SEAOB (Büzmen, Çalı, Pertek, Mamlis - Sin), CACC (Esendemirtepe, Horoz, Karamadazı) and western Anatolia (Kuşçayır, Karatağ, Domaniç - Muratdere) has been formed. Most of the occurrences/mineralization within western Anatolia lies mainly within the Biga (Çanakkale - Balıkesir) region where a continuous intrusive and extrusive magmatism from Eocene to Pliocene are recorded. These are mostly skarn, porphyry to epithermal (to mesothermal?) systems with low sulfidation and high sulfidation characteristics. The skarns are limited and associated with post-collisional volcano-plutonic associations that spans from late Eocene to late Oligocene - Miocene. The sixth metallogenic epoch in the metallogenic history of Turkey corresponds to Middle-Late Oligocene during which the convergence between African and Eurasian plates have been accommodated by Aegean subduction, that produced compression related, arc-type volcano-plutonic sequences mainly at Biga peninsula. This epoch has played an important role mainly on the generation of porphyry (Ağdağ, Tepeoba), Fe-Cu skarns (Evкли, Bayramiç), HS epithermal systems (Pirentepe) with sporadic LS systems (Kuçükküre, IOCG (Şamlı, Demirliitepe), Pb-Zn and Fe-skarns (Baklan, Ayazmancı) and volcanic-hosted mesothermal Pb-Zn vein systems (Balya, Karaköy) within the western Anatolia. The seventh metallogenic epoch have close relationships mainly with alkaline volcanic associations only formed during late Miocene. This epoch is related to only to porphyry (AS and Inlice) and telescoping epithermal systems. The available Ar-Ar geochronology (Kuşçu, 2009; Kuşçu et al., 2013) have shown that the HS, porphyry and LS-type epithermal systems along with some Fe-Cu skarns and LS epithermal (Doğancılar, Kepeş) systems. The eighth metallogenic epoch include a younger phase of magmatism due subduction and subsequent core-complex and/ or roll-back mechanism that took place between Late Oligocene - Early Miocene and Middle Miocene, respectively. The operating major porphyries are associated mainly with extrusive alkaline magmatism at Middle - Late Miocene.

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