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Emplacement of metamorphic core complexes and associated geothermal systems controlled by slab dynamics

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ABSTRACT

Slab rollback results in the development of low-angle normal faults (detachments) and metamorphic core complexes (MCCs) in back-arc domains. Although the mechanical consequences of slab dynamics on lithospheric and crustal behaviors have already been studied, thermal effects have not been investigated yet. This study shows that slab rollback produces lithospheric-scale thermal perturbations intrinsically associated with emplacement of amagmatic high-enthalpy geothermal systems. Using a multi-scale numerical modeling approach, with lithospheric-scale 3-D thermo-mechanical models of subduction, and 2-D models of fluid flow at the scale of detachments, we demonstrate that subduction-induced extensional tectonics controls the genesis and distribution of crustal-scale thermal domes from the base of the crust, and the location of high-energy geothermal systems. We find that when slab tearing occurs, Moho temperatures can temporarily increase by up to 250 °C due to significant shear heating in the flowing upper mantle. Associated thermal anomalies (with characteristic width and spacing of tens and hundreds of km, for crustal and lithospheric scales, respectively) then migrate systematically toward the retreating trench. These thermal domes weaken the crust, localize deformation and enhance the development of crustal-scale detachments. These thermo-mechanical instabilities mimic genesis of high-temperature MCCs with migmatitic cores in the back-arc domain, such as those of the Menderes (western Anatolia, Turkey) and Larderello (southern Tuscany) provinces in the Mediterranean realm, and those in the Basin and Range (western United States), where detachments control the bulk of the heat transport. At the scale of MCCs, the bulk fluid flow pattern is controlled by topography-driven flow while buoyancy-driven flow dominates within the permeable detachments, focusing reservoir location of high-energy geothermal systems at shallow depth beneath the detachments.

1. Introduction

The development of geothermal power plants has been increasing since the 1970s, building upon more than 100 years of history in geothermal energy extraction. Currently, the installed global capacity is estimated at 12.6 GWe (Gigawatt electrical), and forecasts for 2050 point to a worldwide capacity of 140 GWe, approximately 8.3% of total world electricity production (Bertani, 2016). Many of the high enthalpy geothermal resources (HEGRs) that make such an ambitious goal possible are located in the vicinity of subduction zones and volcanic arcs, where both magmatic and tectonic processes operate (Fig. 1). Others are located in "amagmatic" provinces such as the Menderes Massif in Western Turkey and the Basin and Range in the Western United States. Particularly noteworthy for this study is that while geothermal systems associated with magmatism have been studied in detail (e.g. Cumming, 2009) those located in "amagmatic" provinces have received less attention (Moeck, 2014).

Recent to present (i.e. Pliocene–Quaternary) magmatism in the upper crust across the Menderes Massif and the Basin and Range

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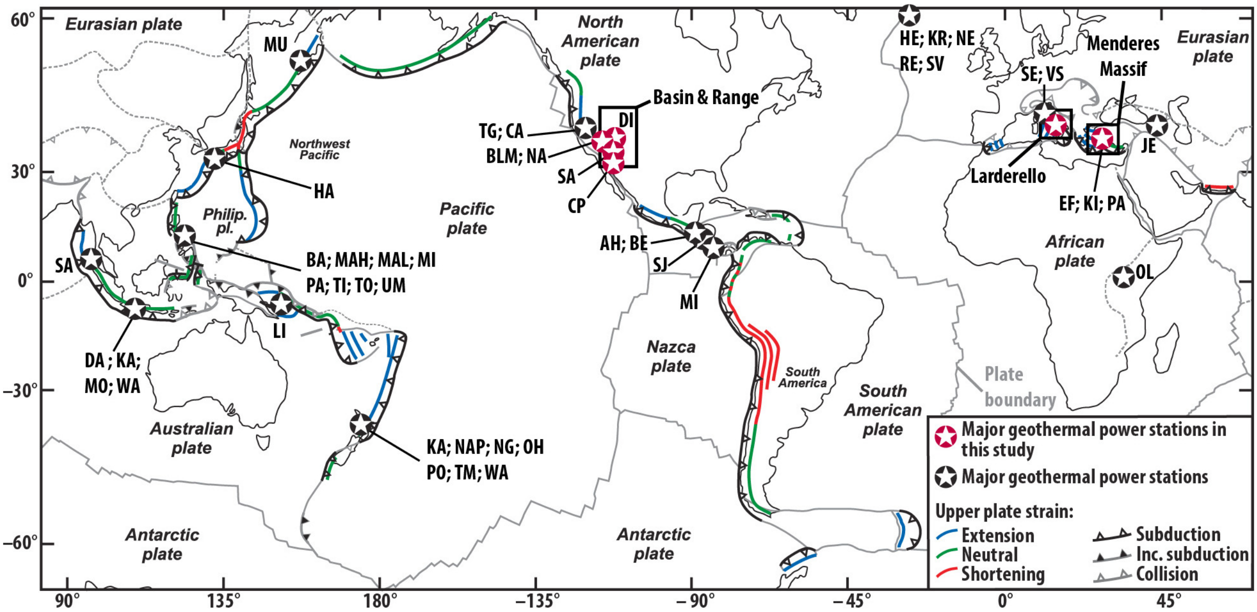

Fig. 1. The major subduction zones on Earth (modified from Schellart et al., 2007). Black stars show the locations of major geothermal power stations that are larger than 50 MWe that are currently operational or under construction. Red stars are reserved for highlighting those within the study areas mentioned in this study. Geothermal stations: JE, Jermaghbyur (Armenia); Mi, Miravalles (Costa Rica); AH, Ahuachapán, BE, Berlín (El Salvador); HE, Hellisheidi, KR, Krafla, NE, Nesjavellir, RE, Reykjanes, SV, Svartsengi (Iceland); DA, Darajat, KA, Kamojang, MO, Mount Salak, SA, Sarulla, WA, Wayang Windu (Indonesia); LA, Larderello, SE, Serrazzano, VS, Valle Secolo (Italy); HA, Hatchobaru (Japan); OL, Olkaria (Kenya); CP, Cerro Prieto (Mexico); KA, Kawerau, NAP, Nga Awa Purua, NG, Ngatamariki, OH, Ohaaki, PO, Poihipi, TM, Te Mihi, WA, Wairakei (New Zealand); SJ, San Jacinto Tizate (Nicaragua); LI, Linhir (Papua New Guinea); BA, Bacman I, MAH, Mahanagdong, MAL, Malitbog, MI, Mindanao I–II, PA, Palinpinon I–II, TI, Tiwi A–B–C, TO, Tongonan 1, UM, Upper Mahiao (Philippines); MU, Mutnovskaya, Russia; EF, Efeler, KI, Kızıldere, PA, Pamukören (Turkey); BLM, CA, Calistoga, DV, Dixie Valley, NA, Navy, SA, Salton Sea, TG, The Geysers (United States). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

is rare (Blackwell et al., 2009; Faulds et al., 2010) compared to that of the Larderello geothermal field, located in the southern Tuscany (i.e. Italy) (Santilano et al., 2015) (Fig. 1). Open discussions on the possible role of hidden magmatic intrusions on these geothermal systems remains debated. Even if present, however, magmatic intrusions alone cannot explain the extent of these geothermal provinces (several thousand km^2 each), and therefore cannot account for high concentration of HEGRs. We must thus identify other sources of heat (deeper and larger-scale) possibly associated with deep, large-scale geodynamic processes involved by the nearby subduction systems.

Slab rollback induces lithospheric extension in the overriding plate where low-angle normal faults (detachments) control both the exhumation of metamorphic core complexes (MCCs) and the magma ascent and/or fluid circulation (e.g. Reynolds and Lister, 1987; Huet et al., 2011). Because detachments may correspond to permeable structures deeply rooted down to the brittle–ductile transition (Famin et al., 2004; Mezri et al., 2015), active extensional domains in back-arc regions could represent favorable settings for HEGRs. The possible sources of heat responsible for regional high temperature–low pressure (HT–LP) metamorphic overprint recorded in these MCCs include (i) heating associated with thermal diffusion of excess heat generated by nappe stacking (increased radiogenic crustal heat, e.g. Bousquet et al., 1997), (ii) shear-heating in the mantle (e.g. Schubert and Yuen, 1978), or (iii) advection of hot asthenosphere to shallow depths during slab retreat (Wannamaker et al., 2008; Jolivet et al., 2015). However, no unifying mechanism responsible for both the generation of MCCs and emplacement of high-enthalpy geothermal systems in the same regions has yet been recognized. This is however a crucial question since HEGRs represent a major economic interest in terms of exploration for carbon-free energy resources.

Here, we first document the self-consistent formation of crustal domes in the overriding plate as a result of thermo-mechanical instabilities in 3-D numerical simulations of ocean-continent subduction dynamics. These models provide crucial thermal constraints for the mantle and crust, and show the importance of shear heating and fast mantle flow on the overall heat budget. Subduction-induced thermal signature in the overriding crust obtained from these experiments is then used as basal thermal boundary condition in 2-D numerical models dedicated to the understanding of fluid flow in the upper crust in presence of detachments that accommodate the formation of these domes. Results show that deep upper crustal hot fluids are drained upward by the permeable detachment. These results will be first compared with geological observations from the Menderes Massif, and then in the discussion, with other cases in the Mediterranean realm (Anatolia and Tuscany) and in the western United States.

2. Geodynamic and geothermal settings of the Menderes Massif

During the Cenozoic, the eastern Mediterranean region (Figs. 2a and 2b) has undergone a two-step tectono-metamorphic evolution. In the late Cretaceous–Eocene, the convergence of Africa and Eurasia first led to the closure of the Izmir–Ankara Ocean. At this time, the accretion of subducting continental and oceanic tectonic units (e.g. Jolivet and Brun, 2010) led to formation of a south-verging crustal-scale orogenic wedge. Since the Oligo-Miocene, collapse of the Hellenides–Taurides belt in this region is mainly controlled by the southward retreat of the African slab, further accelerated in the middle Miocene by a major slab tearing event evidenced by tomographic models below western Turkey (Fig. 2c) (e.g. Piromallo and Morelli, 2003). Extension in the overriding plate has thus led to exhumation of different MCCs such as the Cyclades in the Aegean Sea and the Menderes Massif in western Anatolia, accommodated by crustal-scale low-angle normal faults such as the Simav, Alaşehir and Büyük Menderes detachments (Hetzel et al., 1995; Bozkurt et al., 2011) (Figs. 2b and 2c). Currently, plate kinematics in this region are characterized by more localized extension, mainly controlled by the westward motion of Anatolia (Reilinger et al., 2006) and by N–S extension accommodated by steep normal faults in the Gediz and Büyük Menderes Grabens, both consequences