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Letters

Constraints on fluid origins and migration velocities along the Marmara Main Fault (Sea of Marmara, Turkey) using helium isotopes

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ABSTRACT

Fluids venting from the submarine portion of the Marmara Main Fault (part of the North Anatolian Fault system, Turkey) were sampled in Ti bottles deployed by submersible. The fluids consist of mixtures of fault derived gases, fault related cold seep fluids, and ambient seawater; these components can readily be distinguished using the isotopes of He and the He/Ne ratios. $^3He/^4He$ ratios range between 0.03 ± 0.1 and 4.9 ± 0.4 Ra, indicating that both crustal and mantle derived sources of helium are sampled by the fault. The dominant gas in all the samples analyzed is methane with the abundance of CO_2 below detection ($\leq 2\%$) in the mantle rich (high $^3He/^4He$) fluids. This is in contrast to nearly all mantle derived fluids where the C species are dominated by CO_2. While high CH_4/CO_2 ratios may reflect organic or inorganic reactions within the crust which reduce mantle derived CO_2 to methane, this is not *a priori* necessary: we show that simple dilution of mantle fluids with methane produced within local sediments could result in the high $^3He/^4He$, methane rich gases currently emanating from the fault. This observation is supported by an anticorrelation between $^3He/^4He$ and $C/^3He$, which is consistent with addition of C and ^4He simultaneously to the fluids.

The highest $^3He/^4He$ ratios were found in the Tekirdag Basin, at the foot of the escarpment bordering the Western Sea of Marmara, where seismic data are consistent with the presence of a fault network at depth which could provide conduits permitting deep-seated fluids to rise to the surface. The lack of recent volcanism, or any evidence of underlying magmatism in the area, along with low temperature fluids, strongly suggests that the ^3He-rich helium in these fluids was derived from the mantle itself with the Marmara Main Fault providing a high permeability conduit from the mantle to the surface. Assuming that the mantle source to the fluids originally had a $^3He/^4He$ ratio of 6 Ra, the minimum fluid velocities (considering only vertical transport and no mixing with parentless ^4He) implied by the high $^3He/^4He$ ratios are of the order of 1–100 mm yr^{-1}.

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1. Introduction

Since Kennedy et al. (1997) demonstrated that mantle derived He emanates from the San Andreas Fault, the He isotopic composition of fault-related fluids of numerous different faults has shown that volatiles escape the mantle via crustal pathways (faults) to the surface. This in turn implies the existence of high permeability passages that cross both the mantle–crust boundary and the ductile lower crust. The isotopes of He are ideally suited for tracing these mantle derived fluids at the Earth's surface due to two fortunate circumstances: firstly, the mantle retains isotopically distinct primordial He and, secondly, He concentrations in surface waters are extremely low (He is not retained in the atmosphere and is insoluble in aqueous fluids). As a result, trace inputs of He from the deep earth can readily be identified at the surface, and the source of this He (mantle or crust) can be identified from He isotope measurements.

Frequently, release of mantle He is associated with magmatism and it seems logical that the mantle must melt in order to liberate He (diffusion through solid mantle being too slow to account for the observed fluxes). Escape of mantle-derived He in zones of extension that do not have any obvious association with

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active volcanism is well known (Brauer et al., 2009; Crossey et al., 2009; Kennedy and Van Soest, 2007; Kulongoski et al., 2005; Oxburgh and O'Nions, 1987). These areas (The Eger Rift, Hungary, The Basin and Range province, USA, the Morongo Groundwater Basin, USA, The Pannonian Basin, Hungary) are characterized by high heat flow, thin crust and possible magmatism at depth ('underplating') hence it is not surprising that mantle He percolates to the surface.

The presence of mantle He in regions of active compression not associated with magmatism is less common and more difficult to reconcile with fluid (He) transfer between mantle and shallow crust. Regions of compression/strike-slip faulting are not associated with thinned crust (frequently the reverse) or with heat flow anomalies which might indicate recent underplating by mantle melts. Thus it is difficult to understand how the mantle underlying the fault liberates He (and presumably other volatiles), or how the released volatiles traverse several kms of ductile lower crust. Nevertheless, $\geq$50% of the He along some sections of the San Andreas Fault (SAF), of the Niigata–Kobe tectonic zone and of the North Anatolian Fault is derived from the mantle (Gulec and Hilton, 2006; Gulec et al., 2002; Kennedy et al., 1997; Mutlu et al., 2008; Umeda et al., 2008). Occurrences of such high fractions of mantle He along these faults are in general limited to restricted sections of fault and that, for the most part, these faults are characterized by significantly lower proportions of mantle He (typically 10–20%) in contrast to the more studied higher $^3He/^4He$ localities.

The presence of mantle fluids in faults could also have implications for the faults themselves: the lack of a thermal anomaly on these strike-slip faults is suggestive of low frictional strength (Lachenbruch and Sass, 1980; Zoback and Beroza, 1993) which is inconsistent with the thermomechanical properties of the fault materials. The effective shear stress required for fault slip can be greatly reduced by the presence of high pressure pore fluids. It has been hypothesized that mantle derived fluids could provide a mechanism for weakening strike slip faults (Iio et al., 2002; Kennedy et al., 1997), although calculations suggest the mantle cannot provide sufficient volatiles (Faulkner and Rutter, 2001).

Frequent fluid emissions have been observed on the seafloor of the Sea of Marmara (Géli et al., 2008) closely related to the location of the Marmara Main Fault (MMF), the western extension of the North Anatolian Fault. Thus, the MMF presents an ideal location to study the nature of fault related fluids. Here, we report new data on helium isotopes and concentrations in fluids sampled from the Sea of Marmara. Combined with previous work (Dogan et al., 2009; Gulec and Hilton, 2006; Gulec et al., 2002; Mutlu et al., 2008), the present study provides new insights on the origin of mantle helium in the Western Marmara area.

1.1. Marmara geology and previous work on the NAF

The North Anatolian Fault (NAF) zone in Northern Turkey is a major transform plate boundary that has produced devastating historical earthquakes along its 1200 km length (Ambraseys and Jackson, 2000; Barka, 1992; Sengör et al., 2005). West of Bolu the fault divides into two main strands, the most active being the northern branch between the Gulf of İzmit and Şarköy (Sea of Marmara). The Sea of Marmara is composed of 1000 m deep basins (from east to west: the Çinarcik Basin, the Central Basin and the Tekirdag Basin), separated by two bathymetric highs orientated NE–SW, the Central and Western highs (Fig. 1). Free gas emissions in the Sea of Marmara are common and appear to be influenced by earthquake occurrence (Kuscu et al., 2005). In deeper parts, gas emissions are commonly observed along or near active faults (Armijo et al., 2005; Géli et al., 2008; Zitter et al., 2008). Chemical analysis indicates that the gas is mainly methane, and has two different origins: (1) biogenic in the Çinarçik Basin origin, and (2) thermogenic in the Western and Central Highs, probably originating from Thrace Basin (Bourry et al., 2009).

On the western slope of the Tekirdag Basin (Fig. 1), numerous densely spaced acoustic anomalies were observed rising from the sea bottom (Géli et al., 2008). Based on Ocean Bottom Seismometer (OBS) recordings, clusters of microseismicity were also documented below the western slope of the Tekirdag Basin, suggesting that tectonic strain contributes to maintaining high permeability in fault zones and that the fault network may provide conduits for deep-seated fluids to rise up to the seafloor (Tary et al., 2011). Both observations support the hypothesis that gas is probably leaking from Thrace Basin reservoirs into the Sea of Marmara, following conduits along faults, active or inactive.

The Thrace basin is an active gas and oil-producing province in Western Turkey, with well-studied geology (Perincek, 1991; Siyako and Huvaz, 2007; Turgut and Eseller, 2000), geophysics (Goncuoglu et al., 2000; Huvaz et al., 2007) and geochemistry (Coskun, 1997, 2000; Gürgey, 2009; Gürgey et al., 2005; Hoşgörmez et al., 2005; Şen et al., 2009). The Late Cretaceous–Early Eocene Tethysian evolution of Western Turkey is related to subduction, ophiolite obduction and collision (Okay et al., 2001; Sengör and Yilmaz, 1981). Two major characteristics are of

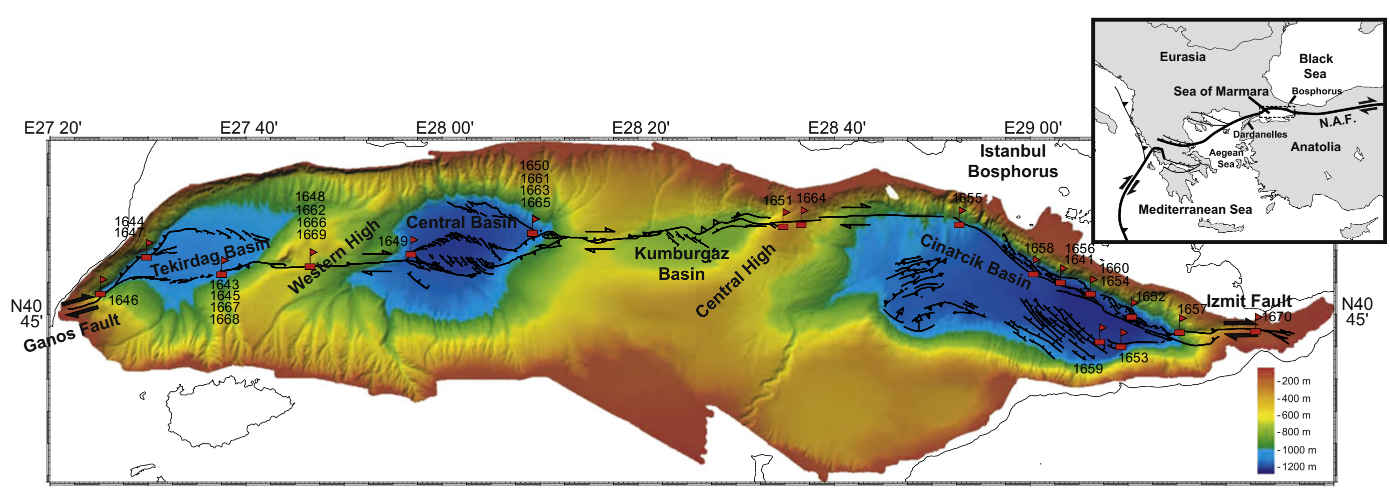

Fig. 1. Sample locations on a bathymetric map of the northern section of the Sea of Marmara. The yellow circle shows the location of well M67 where Dogan et al. (2009) report $^3He/^4He$ ratios up to 4.8 Ra.

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