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New Directions in Seismic Hazard Assessment through Focused Earth Observation in the Marmara Supersite

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Deliverable 2.1

Report on multi-parameter data collection and integration from the Marmara area

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Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (including the Commission)	
RE	Restricted to a group specified by the consortium (including the Commission)	
CO	Confidential, only for members of the consortium (including the Commission)	

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2 SUMMARY

Deliverable D2.1 reports on the multiparameter data collection and integration and includes data of fluid geochemistry, soil degassing, seismicity, and geodetic measurements. The data produced within the MARsite Project are reported in in deliverables D2.2, D2.3 and D2.4. Here they are integrated and discussed all together.

During the activities carried out in the mainframe of MARsite, a significant number of data have been collected by automatic seismic, geochemical and geodetic stations, by periodical measurements of soil degassing and by field works aimed to collect fluid samples and carry out in situ measurements on the fluid phases. A suite of 120 fluid samples from 61 sites in the Marmara region have been collected from thermal and mineral waters (Fig. 1) marking the Northern and Southern branches of the North Anatolian Fault Zone (NAFZ). Samples of free bubbling gases were taken whenever feasible; additionally, water samples with dissolved gases were collected. Gas and water samples were analyzed for the main chemical composition as well as their isotopic composition. A total of about 500 analytical determinations have been carried out at the INGV and TUBITAK laboratories. Details on the gas and water geochemistry are reported in deliverable D2.4.

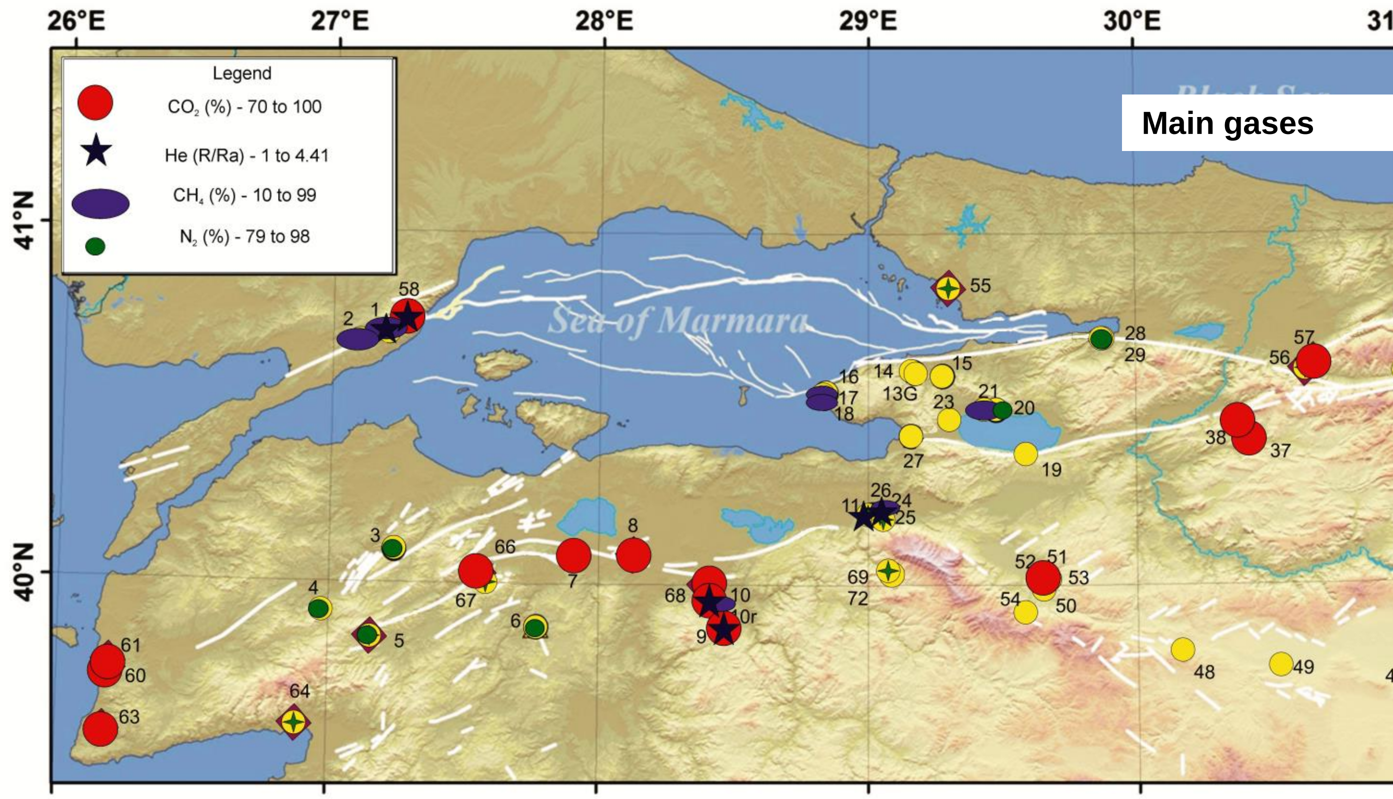


Figure 1 - Fluid samples taken from 61 thermal and mineral water springs/wells during two MARsite fluid monitoring campaigns (2013 and 2014) around the Sea of Marmara. The most abundant gas specie is CO_2 *sometimes associated to high helium isotopic ratios.*

The comparison between CO_2 and CH_4 concentrations and flux distribution maps (Fig. 2) highlights an overlapping of the highest values (CH_4=1.6% CO_2=54% ϕCH_4=8570 mg/m^{2}day and ϕCO_2=12400 g/m^{2}day, respectively) in the Adapazari area (eastern sector of the Marmara area). This site could be more permeable to the gas leaks allowing gas migration along preferential pathways. See deliverable 2.3 for detailed information of the soil degassing. The variability of gas emissions is clearly controlled by the geological structures and thus, repeated flow rate measurements could provide information on possible fault movements in future campaigns.

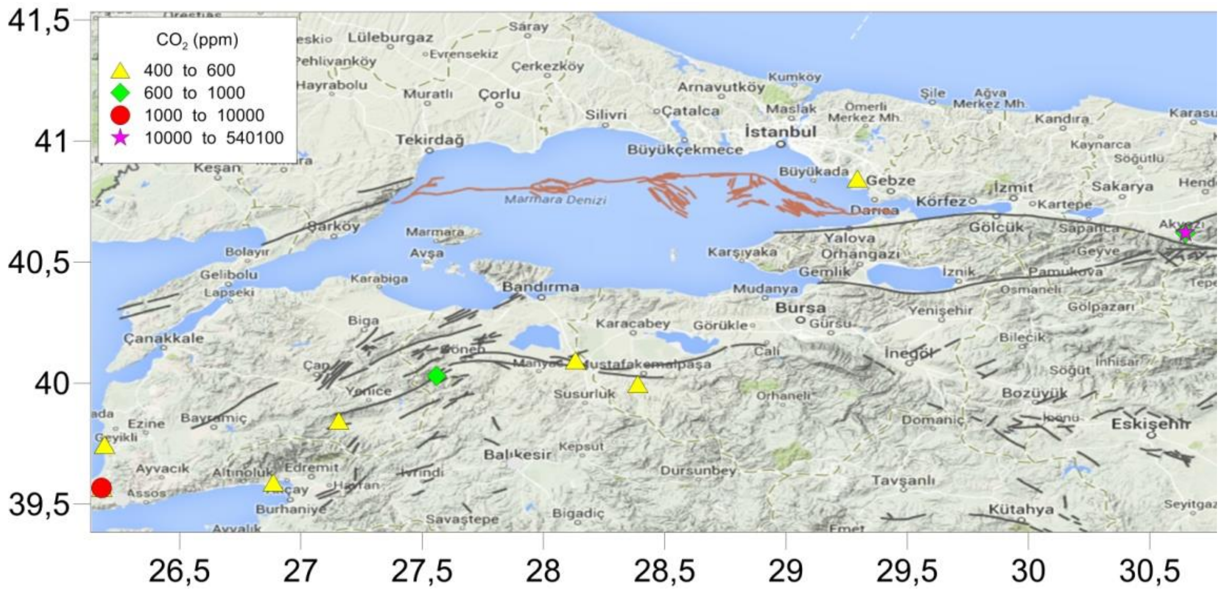


Figure 2 - Distribution of CO_2 concentrations in soil gases

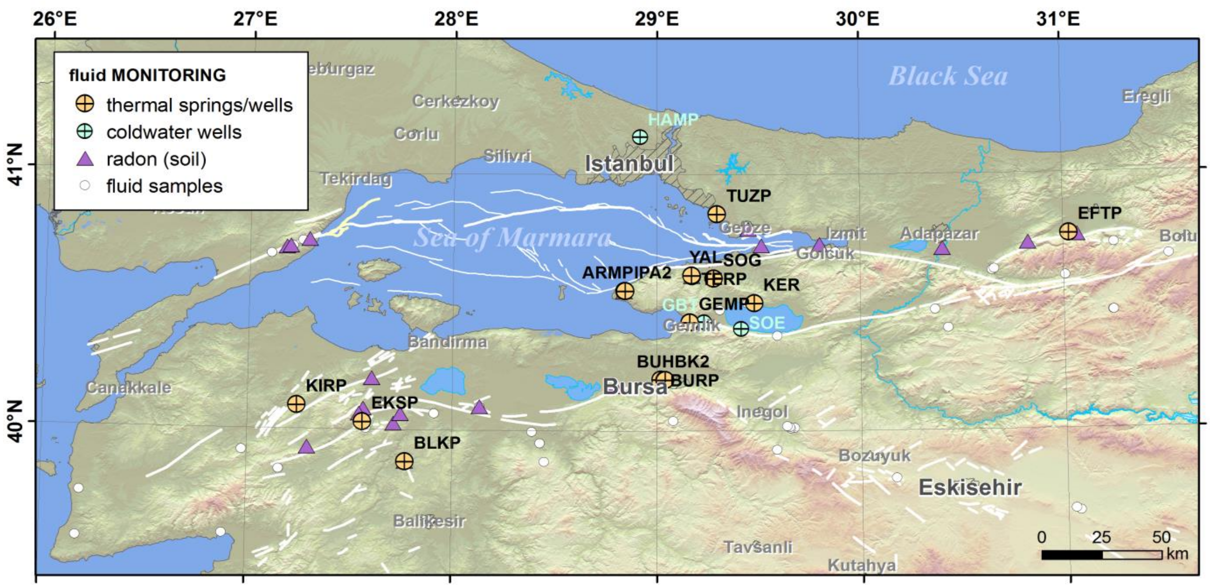


Figure 3 - Distribution of the automatic networks (TABITAK and ARNET) for cold/thermal waters monitoring and soil radon.

The data collected by the two networks for continuous groundwater monitoring (Fig. 3; see deliverable D2.2) indicate that some sites are sensitive to the terrestrial tides and thus they are good observations sites for the effects induced by crustal deformation on the circulating fluids.

Combining together the information on the origin of the circulating fluids (using their geochemical features and isotopic signatures)) their temporal behaviour (using the data from the continuous monitoring networks), the occurrence of significant seismic shocks and geodetic information, it is theoretically possible to gain an insight on the development of the seismogenic process over segments of the active fault system.

The information gained by the fluids geochemistry can be summarized as follows:

1) a widespread degassing of CO_2 marks either the free gas phase and the gases dissolved in the circulating waters;
2) the chemical composition of the gases is affected by the presence of two main components respectively CO_2 and N_2 dominated;
3) the presence of CO_2 testifies that volatiles coming from deep crustal levels are nowadays vented along the various branches of the NAFZ;
4) the helium contents of both dissolved and bubbling gases reveal that the volatiles undergo dissolution phenomena and that helium is a significant component which origin is either related to radiogenic and mantle-type fluids;

5) The chemical composition of the waters is closely related to the interactions with the ground waters hosting rocks and the upraising volatiles.

3 MULTIPARAMETER DATA ANALYSIS

Geophysical, geodetic and geochemical time series including continuous and periodical soil radon gas and groundwater data have been analyzed for possible changes related with seismic activity and/or crustal deformation. Due to the large amount of seismic events (about 6.000; Fig. 4) recorded during the MARsite project, various statistical methods were applied to identify possibly relationships between earthquakes and fluids behaviour.

The evidence that fluids originated in three different domains interact and mix to produce the final composition in terms of both chemical and isotopic composition, leads to the conclusion that, apart from atmospheric gases, around the Marmara area crustal fluids are available as well as mantle volatiles. Moreover, the presence of mantle fluids indicates that some North Anatolian fault segments have a lithospheric character, thus there are the conditions for an upraising of deep-located or deep-originated fluids and for their interaction with ground waters circulating at shallower levels. The fluid circulation is thus a matter of a combination of the geological and tectonic setting of the area. The different geochemical features of the collected fluids are a clear indication for the different settings of the segments of the NAFZ. Water bodies, where deep-originated volatiles may interact, are located in the upper crust normally within the first 3-5km.

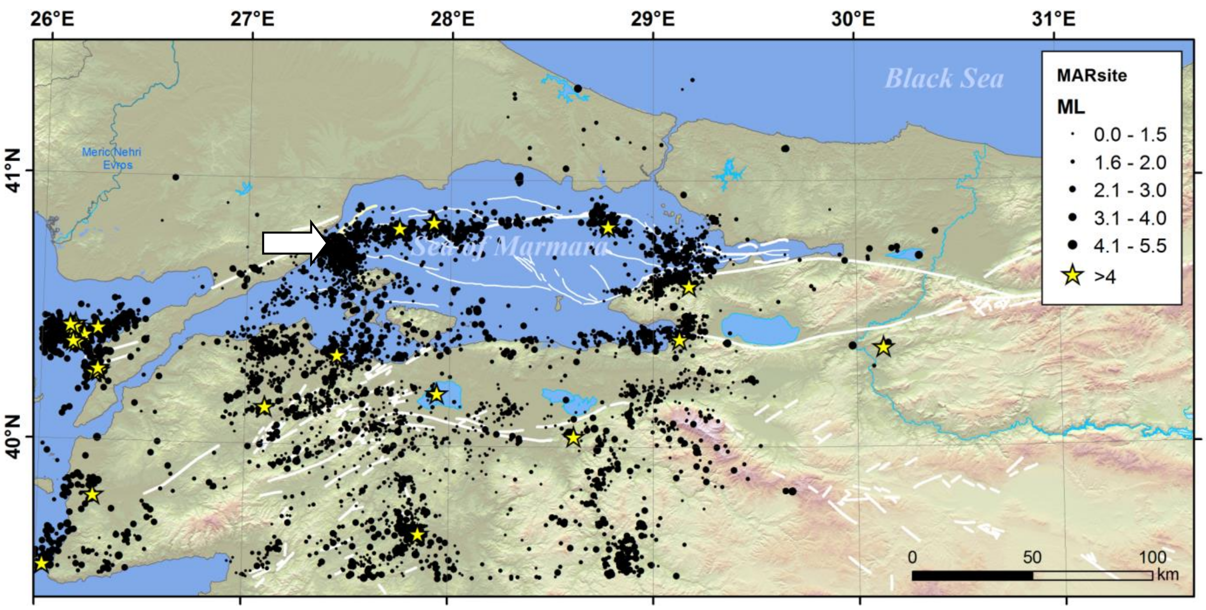
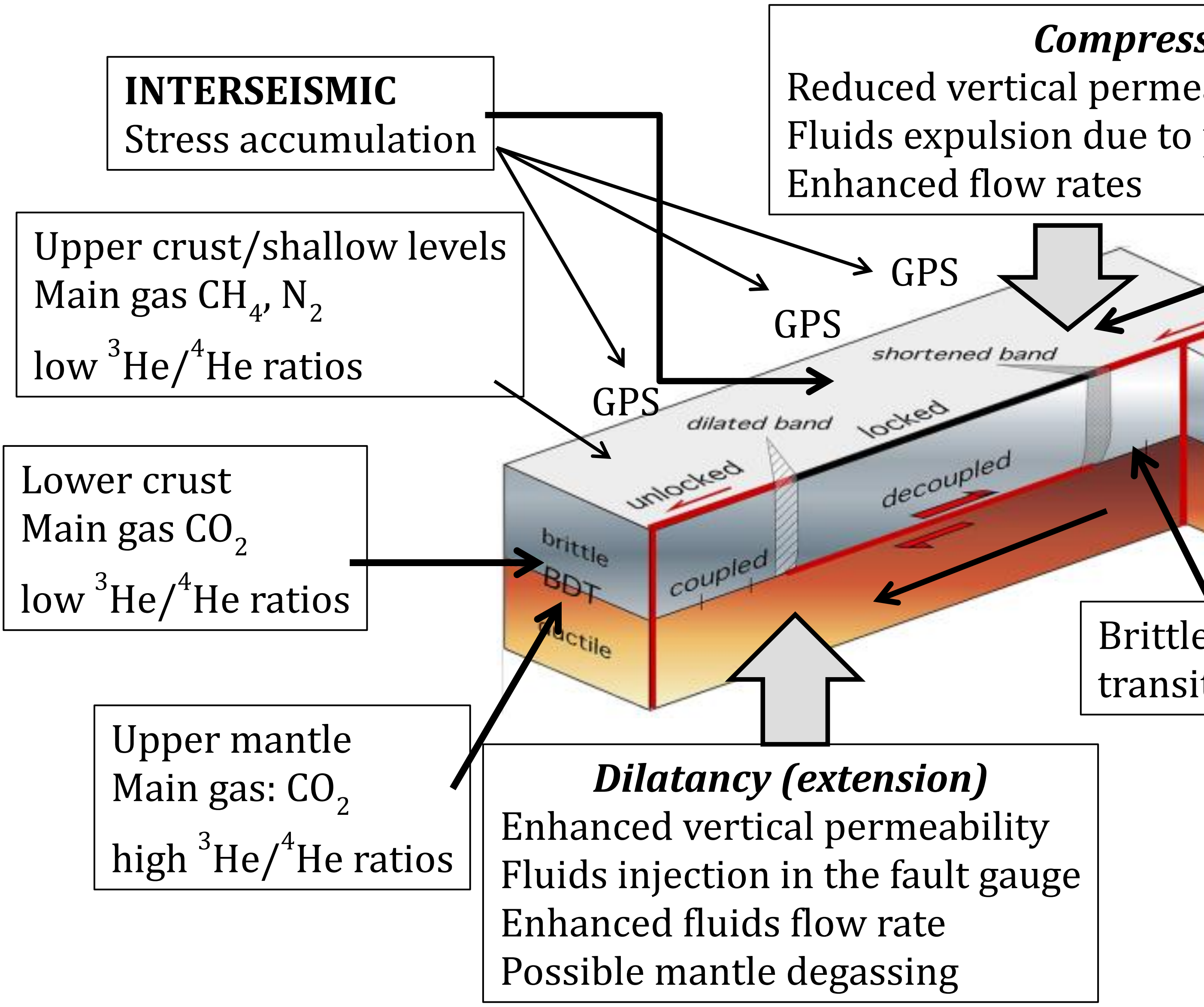


Figure 4 - Epicenter map of earthquakes (M_L ≥ 4.0 events are depicted as yellow stars) occurring in the study area in the period between November 1st, 2012 and February, 29th, 2016. It is worth of notice the

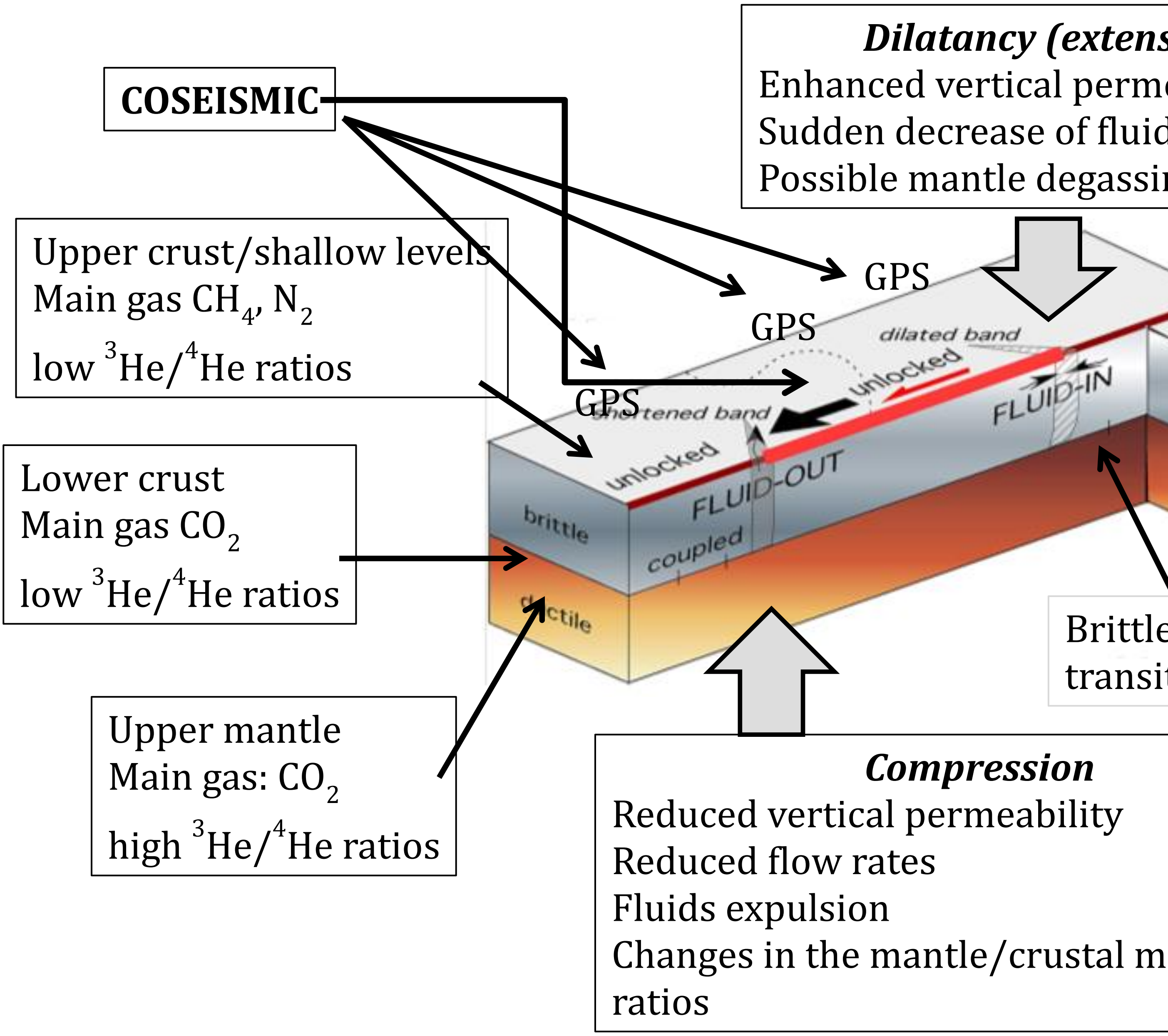
concentration of the seismic activity at the Ganos area (white arrow on the figure) coincides with the highest value of helium isotopic ratio (namely the highest contribution of mantle volatiles).

The composition of the circulating fluids is determined by the local geology due to water-rock interactions with the host rocks where ground waters equilibrate or interact with gases. However, in the case of contributions of mantle fluids it is necessary that deep reaching fractures or faults allow the volatiles to rise to the surface and in this case the composition of the deep fluids is controlled by the tectonic environment.

As a matter of fact, since mantle degassing is not obvious in a non-volcanic area like the Marmara region, we argue that high helium isotopic ratios indicate mantle degassing through lithospheric faults. On the other hand, intense mantle degassing shown by high flow degassing rates at the surface along faults cutting 15-25 km of crustal thickness is not always supported by the vertical permeability (Italiano et al., 2000). Thus, we tentatively argue that the vented mantle-derived fluids may be related to melts intruded at crustal levels as already observed in Southern Apennines (Italiano et al., 2000). Evidence that fluids with a variable - although sometimes significant - mantle component are vented over the whole Marmara region implies a widespread lithospheric character of the various NAFZ branches high-lighting the possibility of detecting changes in the fault behaviour from temporal and spatial changes in the mixing proportion of the deep and shallow fluid components. Following the model proposed by Doglioni et al. (2011, 2014), the Brittle-Ductile-Transition (BDT) zone ideally separates two layers with different strain rates and structural styles. This contrasting behaviour determines a stress gradient at the BDT that is eventually dissipated during the earthquake.


INTERSEISMIC
Stress accumulation
Upper crust/shallow levels
Main gas CH_4, N_2
low $^3He/^4He$ ratios
Lower crust
Main gas CO_2
low $^3He/^4He$ ratios
Upper mantle
Main gas: CO_2
high $^3He/^4He$ ratios
GPS
GPS
GPS
Compress
Reduced vertical perme
Fluids expulsion due to
Enhanced flow rates
shortened band
dilated band
locked
unlocked
decoupled
coupled
brittle
BDT
ductile
Brittle
transit
Dilatancy (extension)
Enhanced vertical permeability
Fluids injection in the fault gauge
Enhanced fluids flow rate
Possible mantle degassing

5a



5b

Figure 5 a, b - Sketch section of a segment of the NAFZ with the BDT zone ideally located at a depth of 15 km where the accumulating stress pushes the upper, brittle layer toward the left. The relative movement of the brittle lower crust to the respect of the ductile upper mantle creates an area where the fault is locked that is compressed on one side and dilated on the other.

At the surface, the different behaviour of the two sides of the fault should be detectable by both GPS and seismic measurements. These two layers also represent two different fluid domains marked by different geochemical features.

The NAFZ-like strike-slip fault displays coexisting, locked and unlocked segments over which two bands with opposite evolution (tension and shortening) form at the tip points of the inactive part of the fault (Figs. 5a-b). Following the model we may assume a simplified two-layer crustal rheology with a constant strain rate on the lower (hot and ductile) crust and episodic locking-unlocking behaviour on the upper (cold and brittle) crust.

During any inter-seismic periods, they perform opposite evolutions (see *a* vs *b* on Fig. 5) inducing different behaviour in fluid circulation and changing both the geochemical features and flow rates. The mixing proportions between crustal and mantle fluids may change even suddenly due to rapid changes in the vertical permeability in coincidence of the compressed-dilated areas at the fault segment tips.

As soon as the shear stress along the locked part of a fault segment exceeds the fault strength, the hanging wall begins to collapse and the fault segment moves toward the rupture and the main shock occurs. During this co-seismic stage the locked fault moves instantaneously, temporarily reversing the strain in the two bands, e.g., the dilated band will be shortened. The fluids are squeezed out in the shortened band and the fluid pressure increases into the fault gouge (Figs. 5a-b). The soil degassing rates and the flow rate of the springs increases, the water level in wells is supposed to rise; the opposite behaviour is expected along the dilated band (Fig. 5b).

Before the rupture, during the inter-seismic period, the proportion of mantle fluids is expected to increase in the dilated band (Fig. 5a) in contrast to an increased fluid expulsion over the shortened area. The contribution of mantle fluids over the same area might decrease during the coseismic period due to the enhancement of shallow fluids expulsion induced by the sudden compression of the dilated band in Figure 5a due to the fault movement. The crustal relaxation of the brittle crust will result in an increase of the mantle fluids uprising over the newly formed dilated band (Fig. 5b). Crustal deformation in dilating areas should be detectable by geodetic measurements.

Fluids of different origin and marked by different geochemical characters circulating at different depths mix in variable proportions as a function of the local vertical permeability that limits the uprising of deep-originated fluids (e.g., mantle fluids). The mixing proportions change if the fluids are located on the locked or unlocked faults due to the different permeability and porosity that mark the compressed and the dilated areas. The possibility of detecting changes in the fluids flow-rates and in the geochemical features over a study area is a matter of changes in the permeability and porosity variations across a rocky body and it is obviously related to the occurrence of fault ruptures (e.g., during co-seismic periods) or, alternatively, to changes in the style of the crustal deformation even in the absence of any rupture.

4 FLUIDS AND CRUSTAL DEFORMATION

The model proposed by (Doglioni et al., 2014) predicts that the inter-seismic strain-rate is lower along the fault segments prone to seismic activation. The GPS velocity field around the Sea of Marmara indicates fault slip rates for the westernmost NAF branches that have generated M>7.1 earthquakes in the past. Those branches are accumulating strain and might be the most likely fault segments to generate future earthquakes. The Izmit and Ganos segments of the NAFZ broke in large earthquakes in 1999 and 1912, and according to (Ergintav et al., 2014) little strain is accumulating at present on both the eastern and western segments of the Central Marmara Fault, most likely due to aseismic fault creep at shallow crustal levels, suggesting these segments have not had sufficient time to generate M7 events in the near future. In contrast, the Princess Islands Fault (PIF) segment is actively accumulating strain and has not experienced any large event since 1766. According to recent hypothesis (Bohnhoff et al., 2013), PIF could be considered the most likely segment to generate a M>7 earthquake, and hence the most imminent seismic hazard to Istanbul and other cities around the Sea of Marmara.

5 CONCLUSIONS

The integration of the collected data bringing together the geochemical features of the circulating fluids in the frame of a geo-tectonic model may provide insights for the selection of future key sites for geodynamic monitoring stations, where equipment to record fluid parameters, deformation as well as seismicity should be co-located. Additionally, periodically-repeated fluid sampling would allow to detect variations occurring during the interseismic periods and their integration with seismic data regarding rupture and/or creeping activity might help to discriminate the origin of the observed changes. The MARsite project enabled us to collect enough data for the evaluation of the background values for the study area. Spatial variations of the $^{3}He/^{4}He$ isotopic ratios are possibly related to rock permeability changes and microfracturing induced by crustal deformations. It is worth of notice that the highest $^{3}He/^{4}He$ value has been recorded in gases dissolved in a cold spring located over the area where seismicity was concentrated (Ganos).

Future studies will show whether the time duration in the $^{3}He/^{4}He$ isotopic ratio anomalies, can be inferred as proportional to the time duration of the crustal deformation processes. We propose that the addiction of mantle-derived helium is not a linear consequence of the occurrence of single seismic events, while providing further support to the hypothesis that the changes in the geochemical features were associated to the whole seismogenic process, accompanied by crustal deformation and microfracturing at depth. As a general consequence, changes in geochemical parameters should be expected during the entire seismogenic cycle, even in the absence of a seismic energy release.

As a matter of fact we can conclude that the data integration indicates the existence of close relationships of the vented volatiles with the geological and structural setting of the Marmara area. The results represent a promising approach for further studies on the origin of the volatiles and their behaviour in coincidence of seismic events and episodes of crustal deformation and may provide new tools to gain a better insight into the evolution of the seismogenic processes over the Marmara area.

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