Proceedings of the 4th Mini Conference on Noble Gases in the Hydrosphere and in Natural Gas Reservoirs held at GFZ Potsdam, GERMANY, 28.02.-02.03.2007

Towards developing the capability for near-continuous sampling and storage of helium in geothermal fluids from regions of crustal unrest

D.R. Hilton[1], E. Furi[1], M.D. Tryon[1], A.L. Labonte[1], and K.M. Brown[1],

[1]Geosciences Research Division, Scripps Institution of Oceanography, La Jolla, CA 92093-0244, USA.

Helium isotopes have great potential in studies related to seismic or magmatic activity. Their utility stems from the wide range in isotopic ratios between mantle-derived He ($^3He/^4He$ ~8R_A where R_A = air He) and He produced in crustal lithologies by radiogenic decay (0.02R_A). Consequently, changes in crustal properties (e.g., permeability) or instances of magma movement, related to either seismic or magmatic unrest, can upset the balance in He inputs from mantle and crustal endmembers resulting in easily-perceived variations in $^3He/^4He$ ratios in crustal fluids such as groundwaters and geothermal waters.

There have been some notable successes in correlating variations in $^3He/^4He$ with the timing, locations and magnitude of earthquakes and volcanic eruptions. For example, (Sano et al., 1986) observed increases in $^3He/^4He$ ratios associated with the 1984 western Nagano earthquake in Japan. In a different study, monitoring of Izu-oshima volcano revealed large increases in $^3He/^4He$ of geothermal fluids (from ~ 1 to 5R_A) following magmatic activity in 1986 (Sano et al., 1995). Italiano and Martinelli, (2001) reported doubling of $^3He/^4He$ values (from 0.02 to 0.04R_A) at Umbria-Marche in the central Apennines, Italy following a seismic crisis in 1997-98. In addition to these examples of He responding in a positive fashion to crustal activity, there are many other cases where He-isotopes show little or no variations in spite of persistent volcanic/magmatic unrest. For instance, studies at Long Valley Caldera from 1986-88 (Hilton, 1996) and along the North Anatolian Fault Zone (NAFZ) from 2002-04 (De Leeuw et al., unpublished data) revealed virtually constant $^3He/^4He$ ratios throughout monitoring periods of ~3-years duration.

DOI: 10.2312/GFZ.mga.010

There are numerous factors that could influence whether He-isotopes respond to crustal disturbances, e.g. magnitude of seismic/magmatic event, distance between event and sampling point, hydrologic controls on fluid mixing, etc: however, one variable which is just as important for recording changes in $^3He/^4He$ values is frequency of sampling. In the study of Italiano and Martinelli (2001), the adoption of a weekly sampling regime was able to catch the He-isotope perturbation following the seismic crises prior to $^3He/^4He$ ratios returning to normal background values within 2 months. Not all He-isotope anomalies are so short-lived, however: Sano et al. (1995) estimated a time-constant for return to pre-seismic He-isotope values of ~ 15 years following volcanic activity at Izu-oshima. It is unknown if the 3-monthly sampling frequency adopted at Long Valley and the NAFZ missed any short-lived He perturbations: sampling/analysis frequency in these cases was limited to 4-times per year.

If He-isotopes are to realize their full potential as a precursory tracer of crustal unrest then a new approach is required that is capable of producing a near-continuous record of He-isotope changes in a natural system without recourse to high frequency (and expensive) sampling. In effect, what is required is an approach that utilizes continuous sampling together with preservation of fluids - to enable specific times of interest (e.g. immediately prior to and/or following a crustal event) to be targeted for detailed, follow-up analytical work. In this way, it should be possible to recognize any anomalous He-isotope signals over a monitoring period irrespective of their duration.

We have developed such a system for deployment on natural cold seeps in the submarine environment. The device consists of a modified CAT-meter (Chemical Aqueous Transport meter; see Figure 1 and description by Tryon et al. (2001). The modification involves the addition of a second osmotic pump, high pressure valves, and copper sample coils to collect and store a temporally-resolved continuous water record for later dissolved He (+ other gases) analysis. The copper coils have virtually zero permeability for He and are held at sea bottom pressure on recovery so that gas losses are negligible. The plastic sample coils are used to collect fluids for non-gas aqueous chemistry and to enable calculation of fluid flow rates. The major ion and flow rate record assist in identifying periods of interest for the more expensive and time consuming gas analyses.

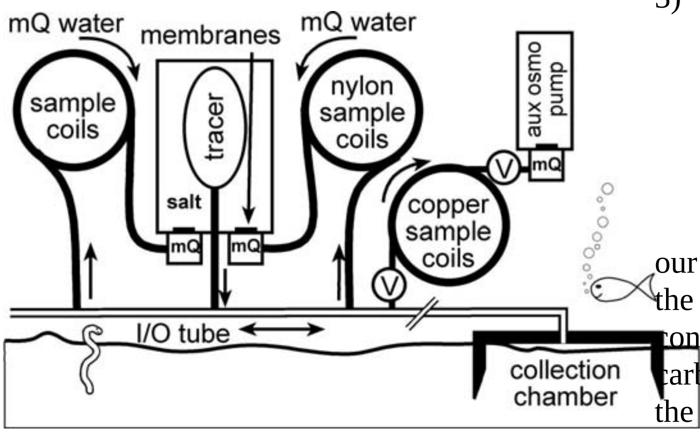

Fig. 1: Schematic of CAT meter. Enhancements to the original CAT meter include the addition of a secondary osmotic pump, copper sample coils, and high pressure valves which automatically shut off on release from the sea bottom.

DOI: 10.2312/GFZ.mga.010

We have deployed the modified CAT-meters at the Extrovert Cliffs site in Monterey Bay, California (Martin et al., 1997). The area is situated close to several active strike-slip faults, including the Monterey and San Gregorio fault zones, and it has many cold seeps located at ~1000m depth. Deployments took place in 2004 and were of ~ 1-3 months duration. Copper coils were processed for both helium and CO_2 (isotopes and abundances) using conventional laboratory methods described previously (Shaw et al., 2003). All samples are supersaturated with respect to seawater in helium and carbon dioxide indicating addition of extraneous CO_2 and He. The main features of the results can be summarized as follows:

1) Air-corrected $^3He/^4He$ ratios vary between ~ $1R_A$ and 2.4 R_A, i.e. between values expected for mantle-derived He (8 R_A) and radiogenic He produced in crust and/or sediments ($0.02R_A$). Using a simple 2-component mixing model for He, up to ~25% of the total He is mantle-derived..
2) For most samples, the $CO_2/^3He$ ratios are significantly greater than anticipated mantle values (MORB ~ 2 $\times 10^9$).
3) There is large range in $\delta^{13}C$ values from -5‰ to ~-25‰. This is consistent with an input of both organic-derived carbon ($\delta^{13}C \approx$ -30‰) and mantle-derived CO_2 ($\delta^{13}C \approx$ -6‰).

Perhaps the most significant result of our deployments, however, is the record of the temporal variation of the He and CO_2 concentration as well as the helium and carbon isotopic composition preserved in the coils. The data demonstrate remarkable temporal variation over days/weeks in the volatile content of the cold seep fluids (Fueri et al., 2005) – these results will be presented at the meeting.

Subsequent to our initial analytical effort, we have refined our laboratory procedures and constructed a dedicated extraction system which can be interfaced directly to the noble gas mass spectrometer. In this way, we can obtain He-CO_2 results on significantly smaller quantities of fluid (< 1 cm^3) thus dramatically improving our time-resolution on He-isotope analysis. Using different sections of the same Monterey coils, we have now obtained a total of 10 combined He-CO_2 analyses which cover a total time period of 1 day (i.e. sampling was achieved with a frequency of ~2.5 hours). Corrected $^3He/^4He$ ratios vary between 1.4 and 3.4 R_A over a single day.

The Monterey results show an unprecedented level of sampling frequency for He-isotopes. The results offer the exciting prospect that geothermal fluids can be collected on an almost continuous basis, with storage for later He analysis at a frequency determined by the seismic or volcanic record. We are presently evaluating the Monterey results with the aim of understanding the processes regulating the inputs (earthquakes, tidal influences, etc.). The next challenge is to adapt the CAT-meters so that they can be used on groundwater wells and subaerial cold and hot springs.

Fueri, E., Hilton, D.R., Brown, K.M., and Tryon, M., 2005, Helium and carbon isotope systematics of cold seep fluids at Monterey Bay (California, USA): EOS Trans. Am. Geophys. Un., p. 160.

Hilton, D.R., 1996, The helium and carbon isotope systematics of a continental geothermal system - results from monitoring studies at Long Valley caldera (California, USA): Chem. Geol., v. 127, p. 269-295.

Italiano, F., and Martinelli, G., 2001, Anomalies of mantle-derived helium during the 1997-1998 seismic swarm of Umbria-Marche, Italy: Geophysical Research Letters, v. 28, p. 839-842.

Martin, J.B., Orange, D.L., Lorenson, T.D., and Kvenvolden, K.A., 1997, Chemical and isotopic evidence of gas-influenced flow at a transform plate boundary: Monterey Bay, California: Journal of Geophysical Research, v. 102, p. 24,903-24,915.

Sano, Y., Gamo, T., Notsu, K., and Wakita, H., 1995, Secular variations of carbon and helium isotopes at Izu-Oshima volcano, Japan: J. Volcanol. Geotherm. Res., v. 64, p. 83-94.

Sano, Y., Nakamura, Y., Wakita, H., Notsu, K., and Kobayashi, Y., 1986, $^3He/^4He$ ratio anomalies associated with the 1984 Western Nagano earthquake: possibly induced by a diapiric magma: J. Geophys. Res., v. 91, p. 12,291-12,295.

Shaw, A.M., Hilton, D.R., Fischer, T.P., Walker, J.A., and Alvarado, G.E., 2003, Contrasting He-C relationships in Nicaragua and Costa Rica: insights into C cycling through subduction zones: Earth & Planetary Science Letters, v. 214, p. 499-513.

Tryon, M.D., K.M. Brown, L.M. Dorman, and A. Sauter, A new benthic aqueous flux meter for very low to moderate discharge rates, Deep-Sea Research I, 48 (9), 2121-2146, 2001.

DOI: 10.2312/GFZ.mga.010