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Supplemental Information

PROCESSING METHODS

At sea, magnetic data acquisition is performed using different methods, depending on the nature of the data. For data collected at the sea surface, a buoyant scalar magnetometer is generally towed at the end of a long and non-magnetic cable, so that the magnetic signature of the ship can be neglected. For deep-sea measurements, the situation is more complex. Indeed, underwater vehicles generally dive at limited altitudes above the seafloor and drape the bathymetry. Towing a long cable would therefore be highly hazardous and the only option therefore consists of fixing a three-component fluxgate magnetometer to the frame of the vehicle.

Because of its close proximity to the magnetometer sensor, the underwater vehicle has a strong influence on the data, i.e., this influence must be quantified and removed to resolve the crustal magnetic anomaly. To estimate the magnetic susceptibility tensor (3x3 square matrix) and the remanent magnetization vector (i.e., a total of 12 coefficients), we use a method proposed by Isezaki (1986) and Honsho et al. (2009). Shortly after the vehicle is dropped into the water, the ship moves away, so that its magnetic influence can be neglected. At that time, the underwater vehicle is still at the sea surface or at shallow depths, and undertakes some calibration figures (often made of Figure-8s followed by a succession of ascents and descents in the N-S and E-W directions). At this very moment, the vehicle is far from both the ship and the seafloor, so that the magnetic measurements should correspond to those predicted by the International Geomagnetic Reference Field (Thebault et al., 2015). All departure from this assumption is seen as a consequence of the magnetic influence of the vehicle. We use this calibration pattern to estimate its influence in a comprehensive range of heading, pitch and roll, and remove it from the data using an improved least square method to finally get the magnetic anomaly.

Because of the Earth's geomagnetic field inclination and declination, magnetic anomalies are phase-shifted and the characteristics of this phase-shift depend on the location of the survey area, i.e., they are impossible to directly interpret. To relocate the magnetic anomalies above their causative sources, a further transformation, called Reduction-to-the-Pole (RTP) is needed. Direct RTP operators exist but they require the data to be collected on a horizontal datum plane, which is not the case for magnetic datasets acquired by underwater vehicles draping the bathymetry rather than keeping a constant immersion. A solution consists in upward-continuing the data to a level datum plane located above the shallowest part of the survey area using the Guspi (1987) method, however such approach acts as a low-pass filter and results in the loss of the hardly acquired signal short-wavelength content. To avoid this loss, we first invert the magnetic anomaly into equivalent magnetization using a Bayesian inversion (Honsho et al., 2012). Unlike older inversion methods, this approach takes full advantage of the uneven trajectory of the vehicle and preserves the whole wavelength content of the signal. We assume a constant magnetization in the vertical direction and choose a 500-m thick magnetized layer. Given the geometry of the dive, such thickness is equivalent to an infinite half-space and all the detectable sources are taken into account. The parameters of the magnetic inversion (magnetic data sampling, interpolation of the bathymetry, determination of the Akaike Bayesian Information Criterion) have been chosen to be consistent with those from the inversions over Lost City and Rainbow, to make a rigorous comparison possible. A mathematically rigorous RTP anomaly is then estimated in the geometry of the experiment using this magnetization and assuming a vertical geomagnetic field (See Fig. DR2).

The positive RTP magnetic anomaly associated with the VDVF is slightly shifted to the North with respect to the current active part of the site. We consider two options to interpret such shift:

1) The hydrothermal conduit is not vertical, resulting in a shifted magnetization production area at depth.
2) A tilt of the underlying crust. It has recently been shown (Szitkar and Dyment, 2015) that a tilt of the basaltic crust would result in a shift of the negative magnetic anomaly associated with a basalt-hosted hydrothermal site sitting on top of it. Nevertheless, this shift can only appear if the site has grown after the tectonic event occurred. In the case of ultramafic-hosted hydrothermalism, an opposite situation occurs. Indeed, hydrothermal sites are producing magnetization rather than destroying the existing one. This "new" magnetization is therefore associated with the local and current characteristics of the magnetization vector. Interpreting a shift of the resulting positive RTP anomaly as a tilt of the underlying block would imply that the tectonic tilt occurred after the site started growing. Given the transient nature of hydrothermal vent fields by comparison with major tectonic events, such hypothesis is extremely unlikely and we therefore consider that the shift of the positive anomaly is most likely a consequence of a non-vertical hydrothermal conduit under the site.

FORWARD MODELING APPROACH

To carry out this study, a forward modeling approach is requested. This method has been developed and used in various articles from Szitkar et al. (2014, 2015, 2017), and is based on a discretization of the bathymetry into prisms. In our case, bathymetric data have a spatial resolution of roughly 5 m. Using the path of the AUV (X, Y and altitude above the seafloor), it is possible to estimate the distance between each prism and the AUV; i.e., to compute their magnetic influence on the magnetometer sensor. As the amplitude of the magnetic anomaly decreases with the cube of the distance, we choose a perimeter of 500 m around each AUV position, as larger perimeters would not produce any noticeable change on the results (For an average altitude of 70 m above the seafloor, the magnetic influence of a prism located at a horizontal distance of 500 m from the AUV is 0.26% of that of a prism located directly under the AUV).

Several parameters impact magnetic models (magnetization intensity, thickness of the magnetized layer and sometimes the presence of a non-magnetic layer of sediments covering the underlying magnetized basement and increasing the distance between the magnetic sources and the magnetometer), i.e., an infinite combination of models produce synthetic magnetic anomalies that match the observed ones. To guarantee the reliability of the results, a nested forward modeling approach is used and the physical hypotheses are kept as simple as possible to avoid any risk of producing 'ad-hoc' models. We also do not try to mimic every short wavelength anomaly, as this would result in making hazardous assumptions. As mentioned above, the first step consists in inverting the magnetic anomalies into equivalent magnetization using the same method and parameters as those used for Rainbow and Lost City to enable a proper comparison (Fig. DR1). The equivalent magnetization within the hydrothermal area clearly dominates and reaches roughly 3 A/m (i.e., stronger than at Lost City), however this contrast virtually never exceeds 1.2 A/m away from the site (Fig. DR1 and DR2).

As the magnetization produced by any inversion method is an equivalent (and not absolute) magnetization, it can either depict real seafloor magnetization variations or variations of the magnetized layer thickness. In order to discriminate between these two hypotheses, we compute the magnetic response of the bathymetry assuming a constant, 1.2 A/m magnetization (Fig. DR3A). The result is logically anti-correlated to the altitude variations of the AUV (Fig. DR3B and DR3C) and does not match the observed anomalies. Nevertheless, since the chosen thickness of the magnetized layer is already equivalent to an infinite half-space, it would be both irrelevant and impossible to arbitrarily adjust it to produce an anomaly that matches the observed one in terms of shape and amplitude. This impossibility underlines the need for spatial variations of the magnetization between the stockwork zone and the surrounding seafloor.

Based on the results from the inversion, it becomes possible to progressively delineate the shape of the magnetized stockwork zone assuming a 500-m thick magnetized layer and a 3 A/m magnetization in the hydrothermal area surrounded by a 1.2 A/m magnetized seafloor. In order to remain physically realistic, we assume that the in-place stockwork zone has a funnel shape and is narrower at its base than in the shallow subseafloor (e.g., Humphris et al., 1996, Herzig et al., 1998). We then progressively iterate until results are reached that match the observed magnetic anomaly. Even if some uncertainties may remain concerning small scale variations of the magnetization, we propose this careful approach as the most precise and reliable way to constrain the non-uniqueness problem of the magnetic forward modeling solutions.

REFERENCES CITED

Guspi, F., 1987, Frequency-domain reduction of potential field measurements to a horizontal plane: Geoexploration, v. 24, p. 87–98, http://dx.doi.org/10/1016/0016-7142(87)90083-4.

Herzig, P.M., Humphris, S.E., Miller, D.J., and Zierenberg, R.A., eds, 1998, Proceedings of the Ocean Drilling Program, Initial reports, Volume 158: College Station, Texas, Ocean Drilling Program, doi:10.2973/odp.proc.ir.158.1998.

Honsho, C. et al., 2009, Magnetic structure of a slow-spreading ridge segment: insight from near-bottom magnetic measurement onboard a submersible: Journal of Geophysical Research, v. 114, BO5101.

Honsho, C. Ura, T., and Tamaki, K., 2012, The inversion of deep-sea magnetic anomalies using Akaike's Bayesian information criterion: Journal of Geophysical Research, v. 117, doi:10.1029/2011JB008611.

Humphris, S.E., et a., 1996, Proceedings of the Ocean Drilling Program, Initial reports, Volume 158: College Station, Texas, Ocean Drilling Program, doi:10.2973/odp.proc.ir.158.1996.

Isezaki, N., 1986, A new shipboard three-component magnetometer: Geophysics, v. 51, p. 1992–1998.

Szitkar, F., Dyment, J., Fouquet, Y., and Choi, Y., 2014a, What causes low magnetization at basalt-hosted hydrothermal sites? Insights from inactive site Krasnov (MAR, 16°38'N): Geochemistry Geophysics Geosystems, v. 15, p. 1441–1451, doi:10.1002/2014.

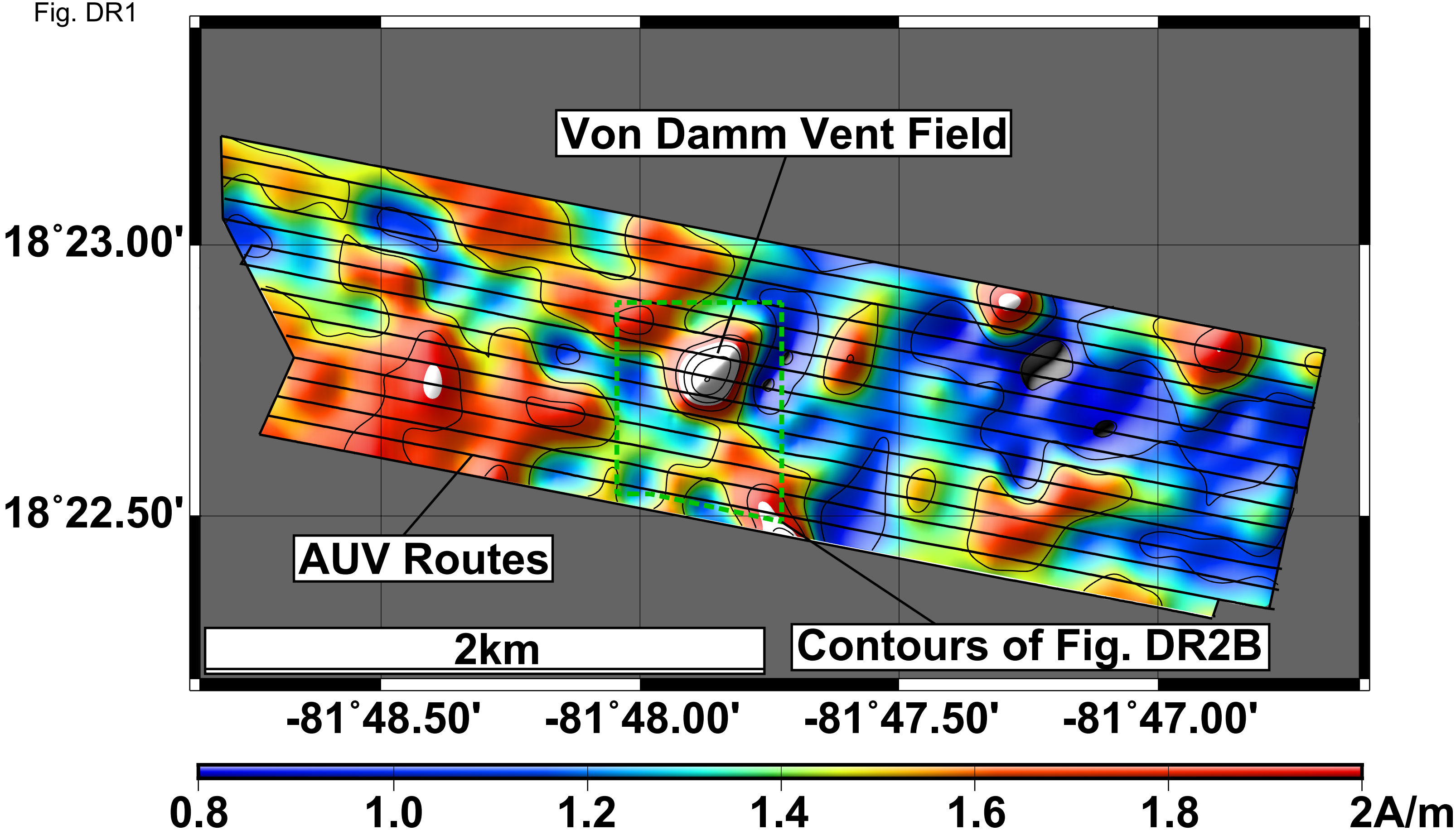
Szitkar, F., and Dyment, J., 2015, Near-seafloor magnetics reveal tectonic rotation and deep structure at TAG (Trans-Atlantic Geotraverse) hydrothermal site (Mid-Atlantic Ridge, 26°N): Geology, v. 43, p.87-90, doi: 10.1130/G36086.1

Szitkar, F., Petersen, S., Caratori Tontini, F., and Cocchi, L., 2015, High-resolution magnetics reveal the deep structure of a volcanic-arc related basalt-hosted hydrothermal site (Palinuro, Tyrrhenian Sea): Geochemistry Geophysics Geosystems, v. 16, doi:10.1002/2015GC005769.

Szitkar, F., et al., 2017, Magnetic exploration of a low-temperature ultramafic-hosted hydrothermal site (Lost City, 30°N, MAR): Earth and Planetary Science Letters, v. 461, p. 40–45, http://dx.doi.org/10.1016/j.epsl.2016.12.033.

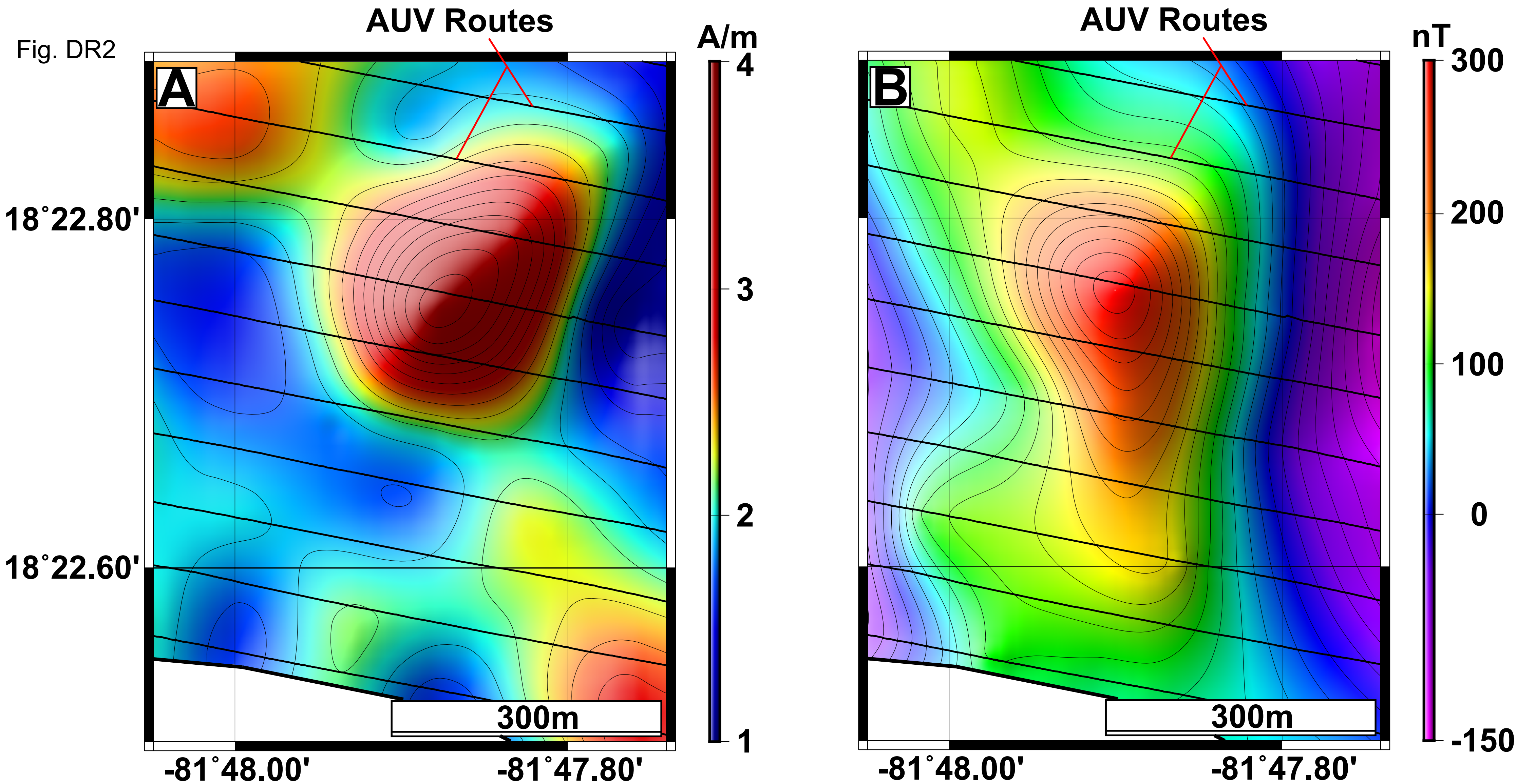
Thebault, E., et al., 2015, International Geomagnetic Reference Field: The 12th generation: Earth Planets and Space, v. 67, https://doi.org/10.1186/s40623-015-0228-9.

Fig. DR1



Equivalent magnetization of the seafloor based on Honsho's Bayesian inversion in the vicinity of the VDVF (Contours: 0.5A/m). The magnetization of the hydrothermal area clearly dominates and largely exceeds the average magnetization of the seafloor. Besides a few other specific areas, the average magnetization contrast away the VDVF area is around **1.2A/m**.

Fig. DR2

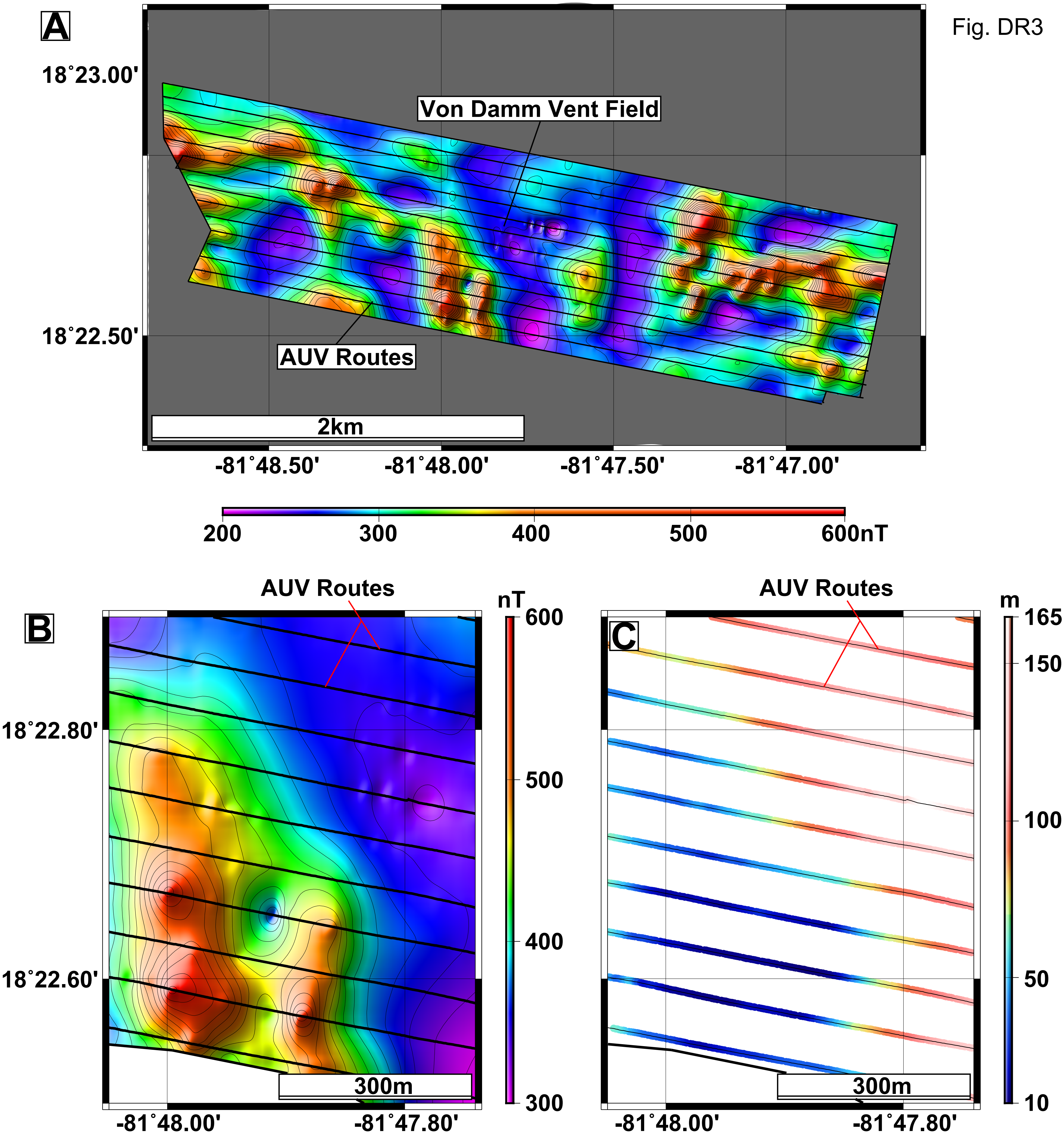


A: Equivalent magnetization of the seafloor using Honsho's Bayesian inversion (Contours: 0.2A/m). The magnetization contrast in the hydrothermal area reaches **3A/m**.
B: RTP anomaly computed from Honsho's Bayesian inversion (Contours: 20nT). The positive magnetic anomaly is in accordance with the magnetic response of other known ultramafic-hosted hydrothermal sites. The lack of a positive anomaly to the southeast corner of the map, despite a positive magnetization contrast results from the higher AUV altitude, i.e., the greater distance between the sources and the magnetometer sensor.

By comparison with the Lost City plumbing system (**2A/m**), the magnetization of the Von Damm Vent Field reveals a logically higher concentration of magnetite. Nevertheless, the limited concentration increase underlines the need for a faster magnetite production rate when temperature rises to account for the observed magnetization at Rainbow (**30A/m**).

We use a 3A/m magnetization to contour the zone affected by serpentinization reaction and keep a 1/2A/m magnetization ewverywhere else.

Fig. DR3



A: Magnetic response of the bathymetry in the geometry of the experiment assuming a constant, 1.2A/m magnetization of the seafloor and a 500m thick magnetized layer, i.e., equivalent to an infinite half-space.

B: Close-up of the above-mentioned model on the hydrothermal area. Neither the shape, nor the amplitude of the synthetic anomaly match those of the observed one.

C: Altitude variations of the AUV along its routes, showing the direct anti-correlation with the amplitude of the synthetic anomaly.