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A multivariate spatial interpolation of airborne γ-ray data using the geological constraints

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ABSTRACT

In this paper we present maps of K, eU, and eTh abundances of Elba Island (Italy) obtained with a multivariate spatial interpolation of airborne γ-ray data using the constraints of the geologic map. The radiometric measurements were performed by a module of four NaI(Tl) crystals of 16 L mounted on an autogyro. We applied the collocated cokriging (CCoK) as a multivariate estimation method for interpolating the primary under-sampled airborne γ-ray data considering the well-sampled geological information as ancillary variables. A random number has been assigned to each of 73 geological formations identified in the geological map at scale 1:10,000. The non-dependency of the estimated results from the random numbering process has been tested for three distinct models. The experimental cross-semivariograms constructed for radioelement-geology couples show well-defined co-variability structures for both direct and crossed variograms. The high statistical correlations among K, eU, and eTh measurements are confirmed also by the same maximum distance of spatial autocorrelation. Combining the smoothing effects of probabilistic interpolator and the abrupt discontinuities of the geological map, the results show a distinct correlation between the geological formation and radioactivity content. The contour of Mt. Capanne pluton can be distinguished by high K, eU and eTh abundances, while different degrees of radioactivity content identify the tectonic units. A clear anomaly of high K content in the Mt. Calamita promontory confirms the presence of felsic dykes and hydrothermal veins not reported in our geological map. Although we assign a unique number to each geological formation, the method shows that the internal variability of the radiometric data is not biased by the multivariate interpolation.

1. Introduction

Airborne γ-ray spectrometry (AGRS) is a fruitful method for mapping natural radioactivity, both in geoscience studies and for purposes of emergency response. One of the principal advantages of AGRS is that it is highly appropriate for large scale geological and environmental surveys (Bierwirth & Brodie, 2008; Minty, 2011; Rybach et al., 2001; Sanderson et al., 2004). Typically, the AGRS system is composed of four 4 L NaI(Tl) detectors mounted on an aircraft. For fixed conditions of flight a challenge is to increase the amount of geological information, developing dedicated algorithms for data analysis and spatial interpolation. The full spectrum analysis (FSA) with the non-negative least squares (NNLS) constraint (Caciolli et al., 2012) and noise-adjusted singular value decomposition (NASVD) analysis (Minty & McFadden, 1998) introduces notable results oriented to improve the quality of the radiometric data. On the other hand, the multivariate interpolation has the great potential to combine γ-ray data with the preexisting information contained in geological maps for capturing the geological local variability.

Elba Island (Italy) is a suitable site for testing a multivariate interpolation applied to AGRS data because of its high lithological variability, excellent exposure of outcropping rocks and detailed geological map. In multivariate statistical analysis, different pieces of information about the particular characteristics of a variable of interest may be better predicted by combining them with other interrelated ancillary information

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into a single optimized prediction model. This approach improves the results of the spatial interpolation of environmental variables. However, sometimes primary and ancillary variables are sampled by different supports, measured on different scales, and organized in different sampling schemes, which makes spatial prediction more difficult.

In this study the collocated cokriging (CCoK) was used in a non-conventional way for dealing with the primary (AGRS data) and secondary (geological data) variables when the variable of interest has been sampled at a few locations and the secondary variable has been extensively sampled. Using this approach, we provide the map of natural radioactivity of Elba Island.

2. Instruments and methods

2.1. Geological setting

Elba is the biggest island of the Tuscan Archipelago and is located in the northern part of the Tyrrhenian Sea, between Italy and Corsica Island (France). It is one of the westernmost outcrop of the Northern Apennines mountain chain (Fig. 1).

The geological distinctive features of this island are linked to its complex stack of tectonic units and the well-known Fe-rich ores, as well as the well-exposed interactions between Neogene magmatic intrusions and tectonics (Bortolotti et al., 2001; Dini et al., 2002; Musumeci & Vaselli, 2012; Trevisan, 1950). The structure of Elba Island consists of thrust sheets stacked during the late Oligocene to middle Miocene northern Apennines deformation. Thrust sheets are cross-cut by late Miocene extensional faults (Bortolotti et al., 2001; Keller & Coward, 1996; Smith et al., 2011).

The tectonics of Elba Island is composed of a structural pile of five main units called by Trevisan (1950) as "Complexes" and hereafter called "Complexes of Trevisan" (TC): the lowermost three belong to the Tuscan Domain, whereas the uppermost two are related to the Ligurian Domain. Bortolotti et al. (2001) performed 1:10,000 mapping of central-eastern Elba and proposed a new stratigraphic and tectonic model in which the five TC were reinterpreted and renamed. TCs are shortly described below.

The Porto Azzurro Unit (TC I) (Mt. Calamita Unit Auct.) consists of Paleozoic micaschists, phyllites, and quartzites with local amphibolitic horizons, as well as Triassic-Hettangian metasiliciclastics and metacarbonates. Recently Musumeci et al. (2011) point out Early Carboniferous age for the Calamita Schist by means of U–Pb and ^{40}Ar–^{39}Ar radioisotopic data. In particular, in the Porto Azzurro area and the eastern side of Mt. Calamita, the micaschists are typically crosscut by the aplitic and microgranitic dykes that swarm from La Serra–Porto Azzurro monzogranitic pluton (5.1–6.2 Ma, Dini et al., 2010 and references therein). Magnetic activities have produced thermometamorphic imprints in the host rocks (Garfagnoli et al., 2005; Musumeci & Vaselli, 2012).

The Ortano Unit (lower part of TC II) includes metavolcanics, metasandstone, white quartzites and minor phyllites. The Acquadolce Unit (upper part of TC II) is composed of locally dolomitic massive marbles, grading upwards to calcschists (Pandeli et al., 2001). This lithology is capped by a thick siliciclastic succession. Ortano and Acquadolce units experienced late Miocene contact metamorphism under low to medium metamorphic grade conditions (Duranti et al., 1992; Musumeci & Vaselli, 2012).

The Monticiano–Roccastrada Unit (lower part of TC III) includes basal fossiliferous graphitic metasediments of the Late Carboniferous-Early

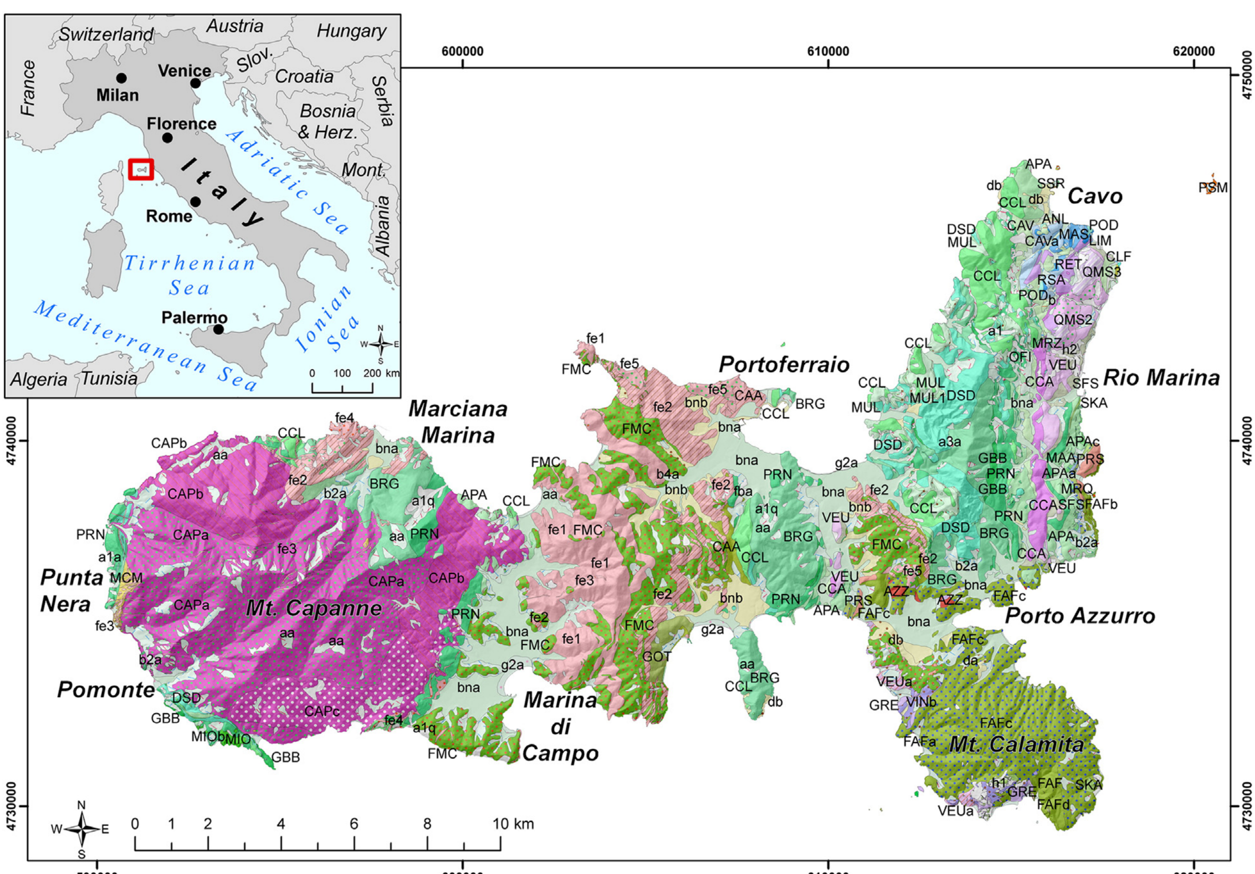

Fig. 1. Geological map of Elba Island (taken from the Geological Map of Tuscany region realized at scale 1:10,000, see CGT, 2011): the western sector is mainly characterized by intrusive igneous rocks (magenta), the central and eastern sectors are characterized by a wide lithological variation (green, purple, and pink), while the southeastern outcrop is constituted almost exclusively of metamorphic rocks (Mt. Calamita). For the legend of the geologic map, see http://www.geologiatoscana.unisi.it. The coordinate system is UTM WGS84 Zone 32 North. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)