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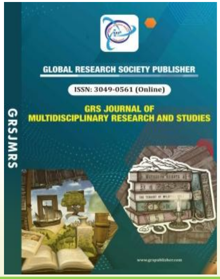

Statistical characteristics of the gravity and magnetic field for the Black Sea region

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Abstract: This study characterizes the spatial statistics, gradients, and lineaments of the gravity and magnetic fields across the Black Sea region to illuminate crustal architecture and tectonic controls. We use satellite-derived free-air gravity grids from the Scripps Institution of Oceanography and the EMAG2 magnetic anomaly grid, resampled onto a common mesh. Within a moving two-dimensional window (31×31 nodes), we compute the first four statistical moments—mean, variance, skewness, and (excess) kurtosis—and compare their spatial patterns. We also estimate horizontal gradients and total gradient direction via local least-squares plane fits, and extract lineaments from maxima of the horizontal gradient magnitude and complementary directional filters. Variance, skewness, and excess sharpen boundaries and reveal fabric that is subdued in the original fields, while gradient-based lineaments delineate probable structural contacts. Regional trends are consistent with published models for Black Sea tectonics and sedimentary basin architecture. The workflow provides a reproducible template for reconnaissance-scale interpretation, resource screening, and hazard assessment.

Keywords: *Black Sea, gravity and magnetic anomalies, EMAG2, satellite altimetry, statistical moments, horizontal gradient, lineaments, kriging*

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Introduction

The Black Sea regino area occupies an intra-continental depression situated between several major tectonic units: to the north — the East European Platform (a stable continental block); to the south — the Anatolian (or Asia Minor) Plate; to the east — the Caucasian orogenic system; to the west — the Balkan–Carpathian orogenic zone. These structures form a complex collision zone between the Eurasian, Arabian, and African lithospheric plates (fig. 1) modified after Okay & Tüysüz (1999); redrawn after Stephenson & Schellart (2010).

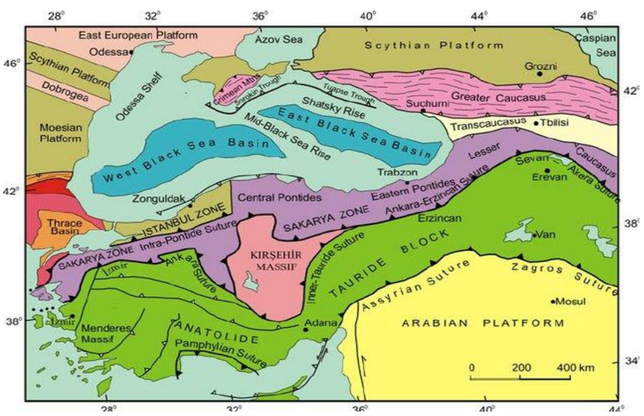

Fig. 1. Regional tectonic map of the Black Sea and surrounding regions, modified from Okay & Tu¨ysu¨z (1999).

The Black Sea basin is a key segment of the Alpine–Tethyan system marked by intricate interactions among accreted terranes, subduction complexes, and rifted domains (e.g., Okay & Nikishin, 2015; Nikishin et al., 2015; Sosson et al., 2016, 2017). Potential-field data—gravity and magnetics—are central to imaging such crustal structure where seismic coverage is sparse or cost-prohibitive. Satellite-altimetry-derived marine gravity has transformed mapping of oceanic and deep-water basins (Sandwell et al., 2014), and global compilations of magnetic anomalies, notably EMAG2, offer consistent coverage at ~2-arc-min resolution (Maus et al., 2009).

Despite numerous regional studies, systematic use of windowed statistics and gradient-based diagnostics to contrast gravity and magnetic fields over the Black Sea remains limited. Here we quantify spatial statistics, gradients, and lineament patterns in both fields. Our objectives are to (i) highlight stationary vs. non-stationary domains; (ii) delineate candidate structural boundaries; and (iii) discuss consistency with published tectonic models (fig.2, 3).

Data

Gravity. We use the satellite-altimetry-derived free-air gravity grid from the Scripps Institution of Oceanography (SIO), which integrates CryoSat-2 and Jason-1 measurements to improve resolution of marine gravity anomalies (Sandwell et al., 2014) fig. 2. These data, collected through satellite measurements, provide comprehensive coverage and high-resolution insights into the gravitational field characteristics of the Black Sea region.

Magnetics. We use EMAG2, a global 2-arc-minute magnetic anomaly compilation referenced at ~4 km above the geoid/ellipsoid, assembled from satellite, ship, and airborne data (Maus et al., 2009; NOAA NCEI, 2009) with a resolution of 2x2 minutes (see Figure 3). The EMAG2 model incorporates a vast array of magnetic field measurements from various sources, including shipborne and airborne surveys, offering a detailed representation of magnetic anomalies across the study area. The initial study window spans 26–43°E and 39–48°N and is trimmed near the margins (27.02–42.01°E; 39.98–47.50°N) to mitigate edge effects. Datasets are projected to a common geographic mesh. To homogenize sampling, we resample the fields by ordinary kriging, a best-linear-unbiased estimator under second-order stationarity (Cressie, 1993; Isaaks & Srivastava, 1989). The working grid contains ~5,000 nodes (~50×100), and all statistical operations are performed on this mesh.

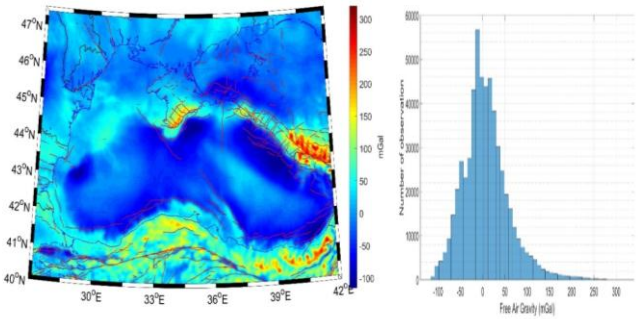

Fig.2. Map of the free air gravity field for the study region (left); histogram plots (right)

The gravity field of the Black Sea region (fig.2) is characterized by localized anomalies, which indicate the presence of geological features such as sedimentary basins, fault zones, and volcanic structures. These anomalies result from variations in mass distribution and crustal thickness, revealing the underlying geological complexity of the region. Understanding the gravity field enables researchers to delineate geological boundaries, identify potential hydrocarbon reservoirs, and assess seismic hazards in the Black Sea area.

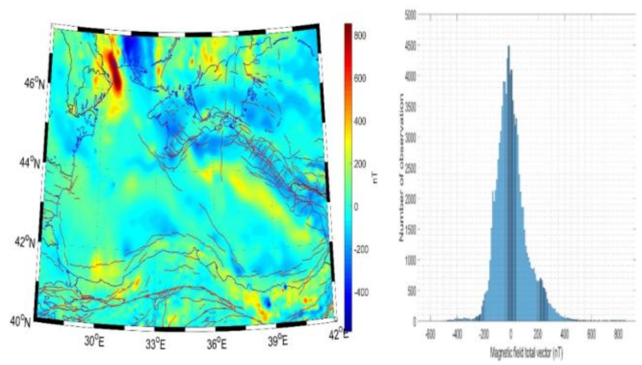

Fig. 3. Map of the distribution and the magnetic field full vector T (left); histogram plot (right)

Overall, the gravity field serves as a fundamental tool for investigating the geophysical characteristics and tectonic evolution of the Black Sea basin, contributing to advancements in geological research, resource exploration, and environmental management.

The magnetic field of the Black Sea region (fig. 3) displays anomalies that reflect variations in magnetization associated with geological features such as igneous intrusions, fault zones, and sedimentary formations. These anomalies serve as proxies for geological boundaries and structural discontinuities, aiding in the interpretation of subsurface geology and the mapping of geological structures beneath the Black Sea.

Understanding the magnetic field enables researchers to identify potential mineral deposits, map crustal faults, and assess the tectonic history of the Black Sea basin. Magnetic data also contribute to studies of seafloor spreading, paleomagnetism, and geomagnetic reversal events, further enhancing our understanding of the geological evolution of the Black Sea area.

In summary, the magnetic field plays a crucial role in unraveling the geophysical characteristics and tectonic history of the Black Sea region, providing valuable insights for geological research, resource exploration, and environmental monitoring.

Methods

Windowed spatial statistics

We decompose the gravity field into a regional component and a local component using an energy-adaptive filter whose base window is chosen from the 2-D autocorrelation radii (r_{0x}, r_{0y}). The local component is further stratified into energy classes (i.e., local variance/mean-square amplitude), and lineaments are extracted separately from the zonal (along parallels) and meridional (along meridians) directional components and then reconciled.

For each node, within a 31×31 moving window we compute: mean (regional trend proxy), variance (field energy), skewness (third standardized moment), and excess (fourth standardized moment minus 3). Variance emphasizes heterogeneous domains; skewness and excess accentuate heavy-tailed distributions often associated with sharp contacts or isolated anomalies. We map each moment for gravity and magnetics to identify stationary vs. non-stationary patches.

Gradient diagnostics

We estimate horizontal derivatives via a local least-squares fit of a plane to each window's center plus neighbors, providing robust $\partial/\partial x$ and $\partial/\partial y$ while suppressing noise amplification typical of simple finite differences. From these we compute the horizontal gradient magnitude (HGM) and the azimuth of the total gradient. Maxima in HGM tend to cluster along edges of density or magnetization contrasts (Cordell & Grauch, 1985; Blakely & Simpson, 1986). For magnetics, we also compute the analytic signal amplitude (conceptually), which is insensitive to magnetization direction in 2-D and also peaks over contacts (Nabighian, 1972; Roest et al., 1992), though we use it mainly as a qualitative cross-check.

Lineament extraction

We extract lineaments by tracing HGM ridges and by combining directional filters applied along parallels and meridians; ridge continuity is enforced with a minimum-length/azimuth-consistency criterion. Intersections and terminations are flagged as candidate transfer zones or fault step-overs. We then compare gravity-derived and magnetics-derived lineament sets to assess structural concordance.

Results

Statistical moments

Across both fields, mean maps capture broad regional trends, whereas variance maps are more segmented and outline domain boundaries. Skewness and excess kurtosis identify focused zones with asymmetric or heavy-tailed distributions—typically coincident with edges of basins/highs or zones of mixed lithology and magnetization. Compared to the original fields, these moments increase contrast along subtle structures that are otherwise smeared by interpolation or long-wavelength trends (fig.4, 5).

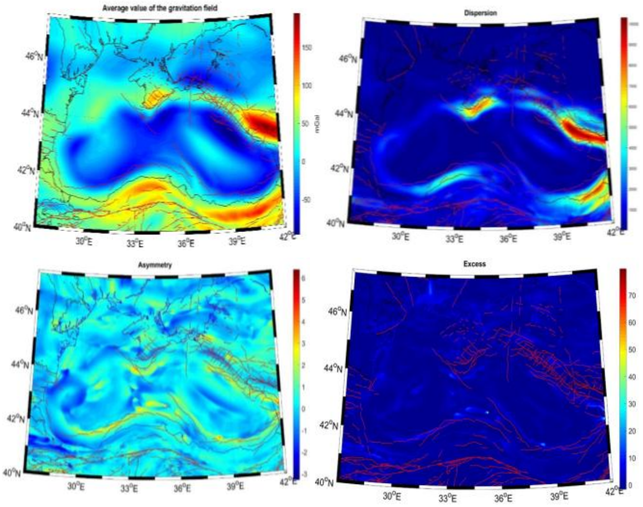

Fig.4. Statistical characteristics of the gravitational field calculated in a sliding window 31x31 points.

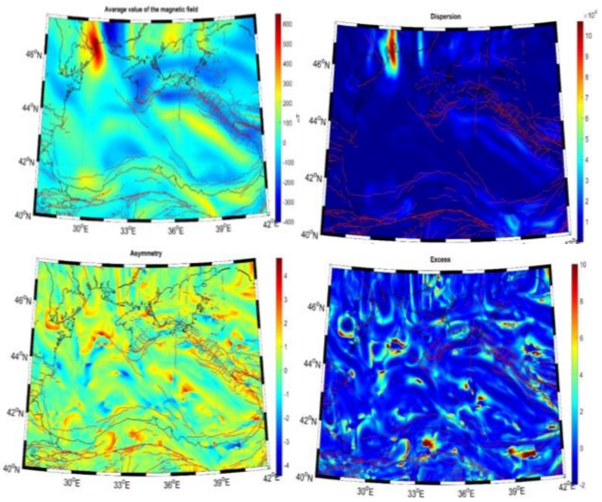

Fig. 5 Statistical characteristics of the anomalous magnetic field calculated in a flat window of 31x31 points.

Gradients

HGM maxima delineate curvilinear belts interpretable as contacts or fault-bounded edges. The gradient-direction field is spatially coherent; sharp azimuth flips track the axes of anomalies and likely fault strikes. Where gravity and magnetics agree on HGM lineaments, the likelihood of true geological boundaries is elevated. Isolated HGM highs in magnetics without gravity counterparts likely reflect shallow magmatic or strongly magnetized bodies (fig.6,7).

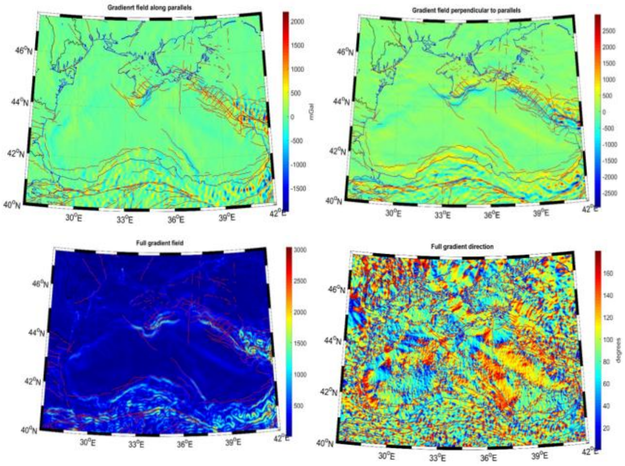

Fig.6. Gradient characteristics of the gravity field for the studied area

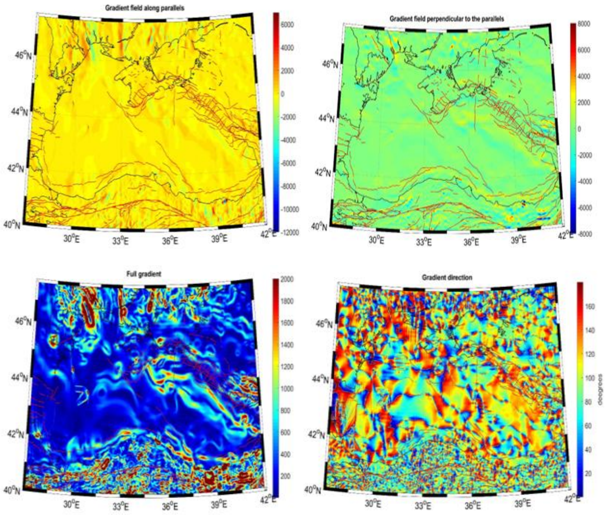

Fig.7. Gradient characteristics of the magnetic field for the studied area.

Lineaments

Merged lineament maps show several dominant trend sets (e.g., broadly NW–SE and ENE–WSW), consistent with documented tectonic structures in the region (Okay & Nikishin, 2015; Nikishin et al., 2015). Lineament density increases along basin margins and intra-basinal highs; cross-cutting relationships suggest multiphase deformation. Where magnetics shows dense short-wavelength lineaments but gravity is smooth, we infer shallow sources or compositional contrasts without large density changes (fig. 8, 9, 10, 11).

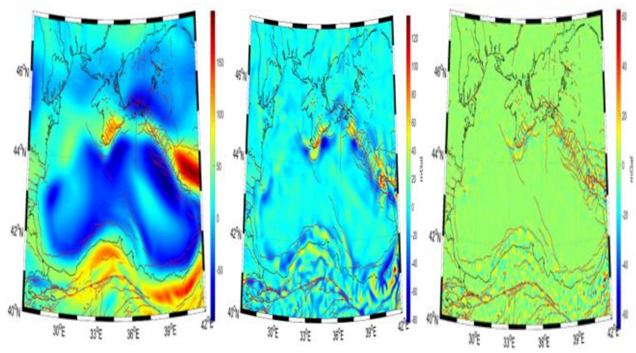

Fig.8. Gravitational fields (local variance) with different energy levels for the studied area; window 31×31.

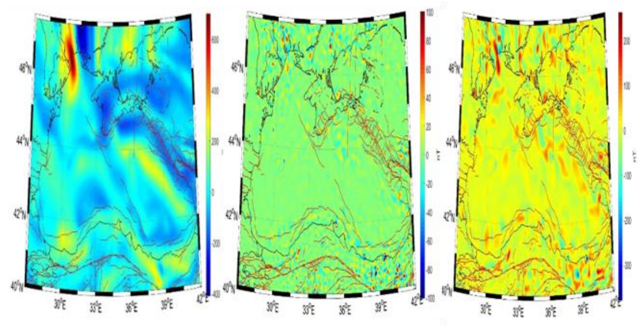

Fig.9 Magnetic field (local variance) with different energy levels for the studied area; window 31×31.

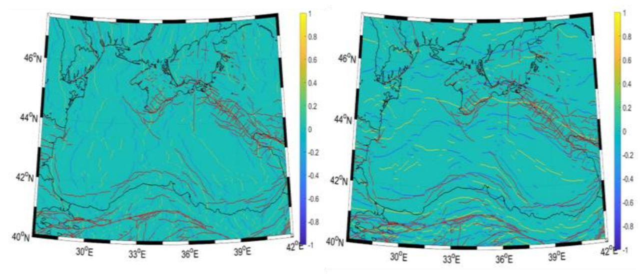

Fig.10 Lineaments of the magnetic fields obtained as a result of dividing the field into constituents. The graphs reconcile the calculated lineaments along the parallels and meridians.

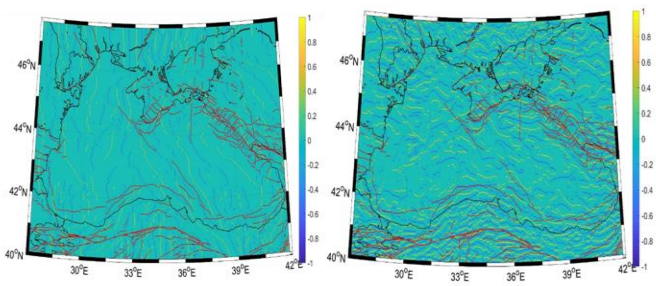

Fig.11 Lineaments of gravity fields obtained as a result of dividing the field into constituents. The graphs reconcile the calculated lineaments along the parallels and meridians.

Discussion

Consistency with regional tectonics. The extracted structures and contacts are broadly compatible with published reconstructions of the Black Sea's rifted basins, intervening highs, and inherited suture zones (Okay & Nikishin, 2015; Nikishin et al., 2015; Sosson et al., 2016, 2017). Our gravity-gradient lineaments tend to outline basin edges and possible fault blocks, whereas magnetic lineaments capture intrusive/volcanic belts and basement lithologic boundaries. The gravity gradients outline basin edges and possible fault blocks of about 70% of the mapped and well known structures. The magnetic gradients are less informative, but covered intrusive/volcanic belts and basement lithologic boundaries 0f about 60%. The combination of both natural fields reach about 75% of all well known structures thus providing high efficiency of the mapping.

Methodological considerations. (i) Window size trades spatial resolution against statistical stability; 31×31 nodes provides a good compromise at our grid spacing, but multiscale windows could recover scale-dependent structures. (ii) Gradient methods are sensitive to noise and to the assumed reduction procedures; local least-squares differentiation mitigates noise but cannot remove aliasing inherited from the source compilations. (iii) The HGM peaks over near-vertical contrasts (Cordell & Grauch, 1985; Blakely & Simpson, 1986); where contacts dip shallowly, peaks may be offset from the true boundary. The analytic signal can help adjudicate such cases (Nabighian, 1972; Roest et al., 1992).

Limitations. Satellite gravity has finite effective resolution tied to altimeter footprint and along-track sampling (Sandwell et al., 2014); EMAG2 inherits variable quality onshore vs. offshore (Maus et al., 2009). Our kriging introduces model dependence (variogram choice); nonetheless, cross-field consistency and robustness tests (median filtering; edge tapering) support the stability of the mapped features.

Applications. The workflow is useful for reconnaissance mapping of structural domains, screening for petroleum play fairways (e.g., basin-margin traps), planning seismic lines, and regional hazard assessment (fault segmentation, potential seismogenic zones). It also provides priors for constrained inversions and basin modeling.

Conclusions

Windowed variance, skewness, and excess of gravity and magnetic fields enhance geologically meaningful contrasts that are muted in the raw fields.

Horizontal-gradient maxima delineate probable edges of density and magnetization contrasts; coherent gradient-direction swings track anomaly axes and likely fault strikes.

Concordant gravity–magnetics lineaments increase confidence in structural interpretations; mismatches flag depth/lithology differences between density and magnetization sources.

Dominant lineament trends (NW–SE and ENE–WSW) align with regional structures reported for the Black Sea system, supporting multiphase tectonic overprints.

Trimming the analysis window and using robust local differentiation reduce edge and noise artifacts, improving the fidelity of gradient and lineament maps.

The combined statistical-and-gradient workflow offers a reproducible, low-cost reconnaissance tool for basin screening, seismic survey design, and hazard mapping.

Future work should (i) explore multiscale windows and wavelet/tilt-derivative attributes; (ii) perform joint gravity–magnetics inversions with cross-gradient constraints; and (iii) integrate seismic and heat-flow data to link structure with basin evolution.

Data availability

Gravity: SIO satellite-altimetry gravity (see Sandwell et al., 2014).

Magnetics: EMAG2 global magnetic anomaly grid at 2′ resolution referenced at ~4 km altitude (Maus et al., 2009; NOAA NCEI dataset page).

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