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Geopolariton tomography of the internal structure of Earth: a passive method for analyzing seismogenic zones

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This study presents geopolariton tomography, a passive geophysical method for investigating the dynamic states of the lithosphere based on event statistics of natural electromagnetic responses. Unlike traditional electromagnetic and seismic approaches, geopolariton tomography does not rely on frequency or amplitude analysis, but employs an event index λ that reflects the intensity of transitions between coupled electromagnetic-mechanical states of the geosphere.

The study introduces geopolariton states as coupled electromagnetic-mechanical responses in which energy is redistributed between electromagnetic and elastic-relaxation modes. Within this framework, the classical skin-depth limitation is addressed at the level of system description: the observed effects are interpreted as stress-controlled modulation and cascading reorganization of coupled states localized primarily within fault-controlled structures rather than as direct electromagnetic penetration from depth.

Using the Bishkek-Tokmak profile (Northern Tien Shan) as a case study, the method reveals volumetric stress clusters and seismic quiescence zones interpreted as dynamically active regimes of elastic energy accumulation. Earthquake hypocentres are shown to form stable parametric ellipsoids, with the most energetic events concentrated near their boundaries, consistent with phase-transition-like processes between energy accumulation and release.

The physical meaning of the event index λ and its nonlinear relationship with the stress-strain state of the lithosphere are discussed. Geopolariton tomography is positioned as a tool for diagnosing pre-critical states and monitoring fault-zone dynamics rather than for deterministic earthquake prediction.

Key words: geopolariton tomography, passive geophysical methods, event index λ, correlation tomography, seismogenic zones, stress-strain state.

Introduction. The study of the deep structure and dynamic states of the lithosphere, especially in the context of seismic hazard assessment, remains one of the most challenging problems in modern geophysics. Despite significant progress in the field of active seismic and electromagnetic tomography methods, their resolutions and sensitivities to slow stress accumulation processes preceding catastrophic ruptures often prove insufficient [Scholz, 2002]. These methods typically capture a static or time-averaged picture of structural heterogeneities, but are poorly responsive to transient precursor states of the geosphere. This problem is particularly acute when interpreting so-called «seismic quiet zones» — areas of temporarily reduced seismic activity, which in classical approaches are often interpreted statistically, without taking into account their potential

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role as dynamically active domains associated with future strong earthquakes [Wyss, Habermann, 1988; Stakhovsky, 2020]. Passive electromagnetic (EM) monitoring of the lithosphere has been investigated for several decades as a potential tool for studying stress evolution and structural heterogeneity in seismogenic regions. Numerous studies have reported electromagnetic anomalies associated with tectonic stress, fluid migration, and rock fracturing processes [Dobrovolsky et al., 1979; Pulinets, Boyarchuk, 2004; Freund, 2011; Varotsos et al., 2011]. These observations indicate that stressed geological media can generate and modulate electromagnetic fields through electrokinetic, piezoelectric, and charge-activation mechanisms.

In this context, the present study does not introduce a new physical phenomenon but develops a phenomenological statistical tomographic framework aimed at improving the interpretation of lithospheric dynamics through the analysis of spatial-temporal electromagnetic variability in fault-controlled environments and the detection of transient states preceding structural reorganization. The approach integrates event-based analysis, introduces a unified diagnostic parameter (λ), and provides a spatial-temporal interpretation scheme for identifying zones of structural instability. It has been empirically established that deformation processes, fracture formation, fluid migration, and stress relaxation in the Earth's crust and upper mantle are accompanied by the generation of electromagnetic signals in a wide frequency range [Hayakawa, Fujinawa, 1994; Johnston, 1997; Freund, 2011]. Numerous observations of precursor EM anomalies, such as changes in atmospheric-ionospheric potential and radiation in the radio and infrasound frequency ranges, confirm a close connection between seismicity and electromagnetic fields [Pulinets, Boyarchuk, 2004; Uyeda et al., 2009; Varotsos et al., 2011]. However, the physical mechanisms underlying this connection, especially in the context of how information related to deep stress states is reflected in near-surface electromagnetic observations, remain a subject of debate.

Rather than assuming direct electromagnetic penetration from depth, contemporary interpretations increasingly consider structural modulation of electromagnetic fields controlled by conductive fault pathways, stress-induced conductivity variations, fluid redistribution, and inductive responses within a heterogeneous lithosphere. Within this framework, electromagnetic observations are treated as indicators of stress-controlled electromechanical coupling processes occurring in faulted geological media.

A fundamental limitation of electromagnetic methods is the restricted penetration depth of high-frequency signals in conductive geological media. Classical EM sounding relies on diffusive propagation, which constrains resolution at depth. The fundamental contradiction can be formulated as follows. According to classical electrodynamics of continuous media, the propagation of a harmonic electromagnetic wave in a conductive lithosphere is limited by a skin layer; its depth δ, for typical conductivity values (σ~0.01÷0.1 S/m) and frequencies characteristic of tectonic processes (f<10 kHz), does not exceed the first few kilometers. This makes it physically difficult to directly explain the correlations between near-surface EM observations and deep processes in the lower crust and mantle, where the hypocentres of the largest earthquakes are located and the main fault systems are formed.

This apparent limitation does not necessarily preclude sensitivity to deep processes; rather, it highlights the need to distinguish between direct electromagnetic wave propagation and indirect field modulation mechanisms controlled by lithospheric structure and stress-dependent conductivity.

Various concepts have been proposed to address this paradox, including models based on nonlinear effects, piezoelectricity, electrokinetic phenomena, and the migration of charged dislocations [Tsapanos, 2001; Molchanov, Hayakawa, 2008; Eftaxias, Potirakis, 2013]. A special contribution to understanding the microphysical basis of seismic-electromagnetic phenomena was made by V.M. Shuman, who emphasized the role of structural and geometric nonlinearity, dispersion, and microheterogeneity of the geoenvironment in generating complex electromagnetic responses [Shuman, 2008, 2015]. However, even within these models, the question of how deep-seated stress states are systematically manifested in near-surface electromagnetic observations through a highly conductive layer remains open.

Recent interpretations suggest that fault zones and fluid-saturated fracture networks may act as conductive waveguides and stress-sensitive modulators, enabling the transfer of structural information from depth via inductive coupling, electrokinetic transport, and stress-controlled conductivity redistribution.

In this work, the method is not interpreted as direct electromagnetic penetration into deep structures. Instead, the observed signals are considered to reflect structural modulation of electromagnetic fields controlled by conductive fault pathways, stress-induced conductivity changes, and inductive responses associated with lithospheric heterogeneity.

Electromechanical coupling in stressed rocks can produce coupled electromagnetic-elastic responses. Stress activation of charge carriers, fluid transport, and microfracturing processes can modify local conductivity and generate transient electromagnetic disturbances.

In the present study, this problem is addressed by introducing a new physical and methodological description level for passive electromagnetic monitoring of the lithosphere. Rather than treating the lithosphere solely as a passive conducting medium for electromagnetic waves, it is considered as an active, hierarchically organized dispersive system capable of supporting coupled electromagnetic-mechanical states, hereafter referred to as geopolariton states. In this context, the term geopolariton is defined as a coupled electromagnetic–mechanical state arising in a stressed lithospheric medium. This definition is consistent with established mechanisms of electromechanical coupling and does not imply a new fundamental particle or wave, but rather a coupled field response within a heterogeneous geophysical system.

Reliable detection of lithospheric EM anomalies requires objective and reproducible criteria. Accordingly, objective event-detection criteria and automated computation of the diagnostic parameter λ are introduced to ensure reproducibility of the analysis. The study also emphasizes the importance of independent validation and blind testing as essential directions for future verification.

Within this framework, impulse events recorded at the surface are interpreted not as attenuated «deep» electromagnetic waves, but as near-surface manifestations of internal reorganization within the spectrum of such coupled states. On this basis, a passive geophysical method — geopolariton tomography (GPTS) — is formulated, which extends the diagnostic capability of electromagnetic observations beyond the limitations imposed by direct wave attenuation and is focused on diagnosing pre-critical stress–strain states of the lithosphere through the analysis of spatio-temporal statistics of natural electromagnetic response events. GPTS is positioned in this study as a phenomenological monitoring and diagnostic system rather than a deterministic prediction method.

The aim of this study is to present the physical foundations, methodological principles, and initial practical results of GPTS as a tool for diagnosing dynamic states of the lithosphere. The active tectonic region of the Northern Tien Shan (the Bishkek-Tokmak profile), characterized by high seismic activity and complex geodynamics, was selected as the key object for testing and illustrating the proposed approach. To evaluate the proposed framework, passive electromagnetic measurements were conducted along the Bishkek-Tokmak profile using a multi-component recording system. The methodological workflow includes acquisition of natural EM emission signals, event detection and classification, computation of the diagnostic parameter λ, and spatial-temporal statistical analysis. The following section describes the instrumentation, data processing procedures, and analytical criteria used to ensure reproducibility and objective interpretation.

Materials and Methods. ***Physical concept of geopolariton.*** To support the physical interpretation proposed below, passive electromagnetic measurements were conducted using a multi-component induction recording system designed for low-frequency lithospheric emissions. The recording system operates in the 1—100 kHz frequency range (ELF—VLF/LF band) with a magnetic field sensitivity of approximately $1\cdot10^{-6}$ A/m, enabling detection of weak lithospheric electromagnetic emissions. Sensor orientation was fixed relative to geographic coordinates to ensure reproducibility of spatial measurements. Data were acquired under conditions minimizing anthropogenic electromagnetic interference. The selected kilohertz frequency range is sensitive to microfracturing processes, electrokinetic phenomena, and charge activation in stressed rocks, which are known sources of lithospheric electromagnetic emissions. Similar frequency bands have been reported in studies of VLF electromagnetic emissions associated with rock fracturing and pre-seismic activity [Hayakawa, Molchanov, 2002; Eftaxias et al., 2009].

In condensed matter physics, polaritons are defined as hybrid quasiparticles that arise when the electromagnetic field interacts strongly with collective excitations of the medium — phonons, plasmons, and excitons [Hopfield, 1958]. By analogy, the concept of a geopolariton is introduced to describe the geoenvironment as an intrinsic hybrid state of the «electromagnetic field-elastic-relaxation» system. The key point is that a geopolariton is not a simple superposition of waves; its existence is determined by strong coupling and energy redistribution between subsystems [Kavokin et al., 2017].

Here, the term geopolariton is used in an operational sense to describe coupled electromagnetic–mechanical responses in a heterogeneous stressed medium and does not imply the existence of a new fundamental quasiparticle. This analogy provides a convenient framework for describing coupled field responses in heterogeneous geophysical media.

The geological environment, lacking a periodic lattice, is characterized by a developed hierarchy of collective degrees of freedom: microdeformations of the mineral framework, oscillations in fluid-saturated zones, relaxation processes at grain contacts, dipole and ion polarization [Biot, 1956; Nur, Simmons, 1969; Pride, 1994]. The combination of these processes forms a continuous spectrum of elastic-relaxation modes that can effectively interact with a low-frequency electromagnetic field.

These relaxation processes create conditions for stress-dependent modulation of electromagnetic fields observable at the surface as measurable electromagnetic responses. The dynamics of such a system can be described by generalized equations that take into account dielectric memory and the connection with mechanical degrees of freedom. The formulation is consistent with Maxwell's equations in media with memory and electromechanical coupling.

The electric induction vector **D** is represented as:

$$\mathbf{D}(r,t)=\varepsilon_0 E(r,t)+ \\ +\int_0^{\infty}\varepsilon_{\mathrm{eff}}(\tau)E(r,t-\tau)d\tau+\mathrm{Pu}(r,t), \qquad (1)$$

where Pu is polarization caused by elastic and relaxation processes. In frequency representation, the wave equation takes the form:

$$\nabla^2 E+\left(\omega^2/c^2\right)\varepsilon_{\mathrm{eff}}(\omega)E=0\,. \qquad (2)$$

At kilohertz frequencies, classical skin-depth limitations restrict diffusive wave penetration; however, the present framework considers stress-controlled modulation and inductive coupling rather than direct wave propagation from depth, where the effective dielectric permittivity includes contributions from various relaxation and resonance processes:

$$\varepsilon_{\mathrm{eff}}(\omega)=\varepsilon_{\infty}+\sum_i\left[\Delta\varepsilon_i/(1-i\omega\tau_i)\right]+ \\ +\sum_i\left[\frac{g_i^2}{\omega_{\mathrm{u}.j}^2-\omega^2-i\gamma_j\omega}\right], \qquad (3)$$

where γ_j is the damping (loss) coefficient of the j-th resonant mode (accounting for dissipative losses and determining the resonance line width and absorption).

The last term in (3) describes the hybridization of electromagnetic and elastic relaxation modes and leads to the formation of dispersion branches of geopolaritons.

Overcoming the skin layer limitation: cascade transmission and the role of faults. The classical skin depth $\delta(\omega)=\sqrt{(2/(\mu_{\subset}\sigma\omega))}$ for a conductive lithosphere limits the penetration of harmonic electromagnetic waves to shallow depths in conductive media. In the geopolariton model, energy and information are transferred not by direct wave propagation, but through a sequence of transitions between bound states (cascade transmission).

The energy participation coefficient of the electromagnetic component $\eta_{EM}(\omega)\in[0,1]$ determines the fraction of the total energy of the hybrid state attributable to the electromagnetic part. The damping length of the hybrid mode can be estimated as $L_{gp}(\omega)\approx\delta(\omega)/\eta_{EM}(\omega)$. Near the resonances of elastic-fluid modes, η_{EM} decreases, energy is transferred into the mechanical subsystem, which reduces the influence of ohmic losses and forms «transparency windows» — frequency intervals with increased hybrid state duration, which should be regarded as an effective attenuation scale rather than a strict propagation length.

Fault zones and fluid channels play a key role in ensuring deep connection. Their increased fracturing, porosity, and fluid saturation increase the density of elastic-relaxation modes and enhance electromechanical coupling. In an approximate model, a fault may act as a preferential channel for coupled electromagnetic-mechanical energy transfer for geopolariton states, facilitating their effective coupling between deep sources and near-surface observation points [Tsapanos, 2001].

GPTS method and event index λ. The GPTS method is based on the recording and analysis of the flow of natural pulsed electromagnetic events. Instead of analyzing amplitudes or frequencies, the event index $\lambda(t, r)$ is used — a normalized number of events exceeding the detection threshold per unit of time at the observation point r. The index is computed automatically using uniform detection criteria to ensure reproducibility and minimize operator bias.

Within the λ model, the spectral density of available geopolariton states $D(\omega, r)$ and the effective transition rate between them $\Gamma(\omega, t, r)$, which depends on the stress state, fluid regime, and structure of the medium, are determined:

$$\lambda(t,r)\approx\int D(\omega,r)\Gamma(\omega,t,r)\,d\omega\,. \qquad (4)$$

Equation (4) represents an effective phenomenological formulation linking event occurrence with the density of available relaxation states and their transition activity.

A decrease in λ is interpreted not as a lack of activity, but as a narrowing of the spectrum of available relaxation paths, an increase in the coherence of the system, transition to a state of increased coherence and reduced relaxation diversity («active calm»).

An increase in λ indicates an increase in relaxation pathways and may reflect progression toward a critical state.

Tomographic reconstruction consists of constructing two-dimensional or three-dimensional distributions of the averaged λ index along a profile or network of observations, which allows visualization of areas with different dynamic states of the geosphere. Spatial averaging and statistical smoothing are applied to distinguish persistent structural patterns from stochastic fluctuations.

Geological and tectonic characteristics of the Bishkek-Tokmak profile. The Bishkek-Tokmak profile, which crosses the northern part of the Chuy Depression and the southern spurs of the Kyrgyz Range in the Northern Tien Shan, was selected to test the method. This region is a well-studied area of active intracontinental mountain building, characterized by high rates of modern deformation (up to 10—15 mm/year) and seismicity [Abdrakhmatov et al., 1996; Yang et al., 2008].

The profile is sublatitudinal and crosses a number of large tectonic structures:

– the Issyk-Ata Fault is the main regional right-lateral strike-slip fault separating the Tien Shan mountain structure from the Chuy Depression. This fault plays a major role in regional stress redistribution and seismic activity;

– Tokmak structural node — the zone where the Issyk-Ata fault intersects the northeast-trending system, characterized by abnormally high fluid saturation and microseismicity and considered a zone of structural complexity and stress concentration;

– the system of thrust faults on the southern edge of the Chuy Depression, associated with the intrusion of the Tien Shan into the depression;

– the deep structure of the region is complicated by the presence of a seismofocal zone extending beneath the Chuy Depression to a depth of 50 km or more, where earthquake hypocenters with $M>5.0$ are recorded [Vinnik et al., 2002]. The region is characterized by a complex stress regime combining shear and thrust components. The presence of thick sedimentary covers in the depressions and intense fracturing in the rocks create conditions for the development of extensive fluid systems, which, according to the current understanding, play a key role in the trigger mechanism of seismicity. GPTS data were collected using a broadband DSF recording system [Prokopenko et al., 2022], shown in Fig. 1.

The equipment is a three-component scanner that records impulsive magnetic-field variations within a broad kilohertz frequency band. An adaptive threshold algorithm [Chen et al., 2022] sensitive to short (0.1—10 s) impulse anomalies against the background of natural and man-made noise was used to select events. The detection procedure was fully automated to ensure reproducibility and minimize operator bias.

Fig. 1. External view of the DSF recording system.

For comparative analysis, a catalog of earthquake hypocenters for the observation period compiled by the Kyrgyzstan seismic station network was used.

Results. ***Tomographic model and volumetric stress cluster.*** Fig. 2 shows a tomographic model of the distribution of the event index λ along the Bishkek-Tokmak profile. Against the background of general spatial heterogeneity, a linearly extended anomaly can be distinguished, coinciding with the direction of regional tectonic structures. The central part of this anomaly is characterized by minimum values of λ.

This zone is interpreted as the core of a volumetric stress accumulation zone. According to the model, the decrease in λ in the core corresponds to a state of increased coherence of geopolariton states and a decrease in the intensity of relaxation transitions, i.e., consistent with increased elastic energy accumulation.

The spatial position of this anomaly correlates well with the projection onto the surface of the deep seismofocal zone, suggesting a possible connection with processes in the lower crust.

Spatial organization of seismicity and parametric invariants. Analysis of the spatial distribution of hypocenters (Fig. 3) shows that they are concentrated on the periphery of the identified cluster and in fault zones, while the inner part of the cluster (the zone of minimum λ) is a zone of seismic quiescence.

For quantitative analysis, the hypocenters were considered in a parametric space including the event index λ and local order characteristics. In this space, the hypocenters form stable ellipsoidal regions, the geometry of which is preserved when the time window of analysis is changed.

In the parameter space (K, FD(CX), φ), the epicenters of earthquakes form three stable clusters. Two of them correspond to the western and eastern blocks, characterized by moderate fractal dimension (FDCX≈0.59) and stable mean phase φ. The third cluster, characterized by FDCX≈0.92 and a distinct phase φ, corresponds to the fault core, where the geopolariton response exhibits the high-

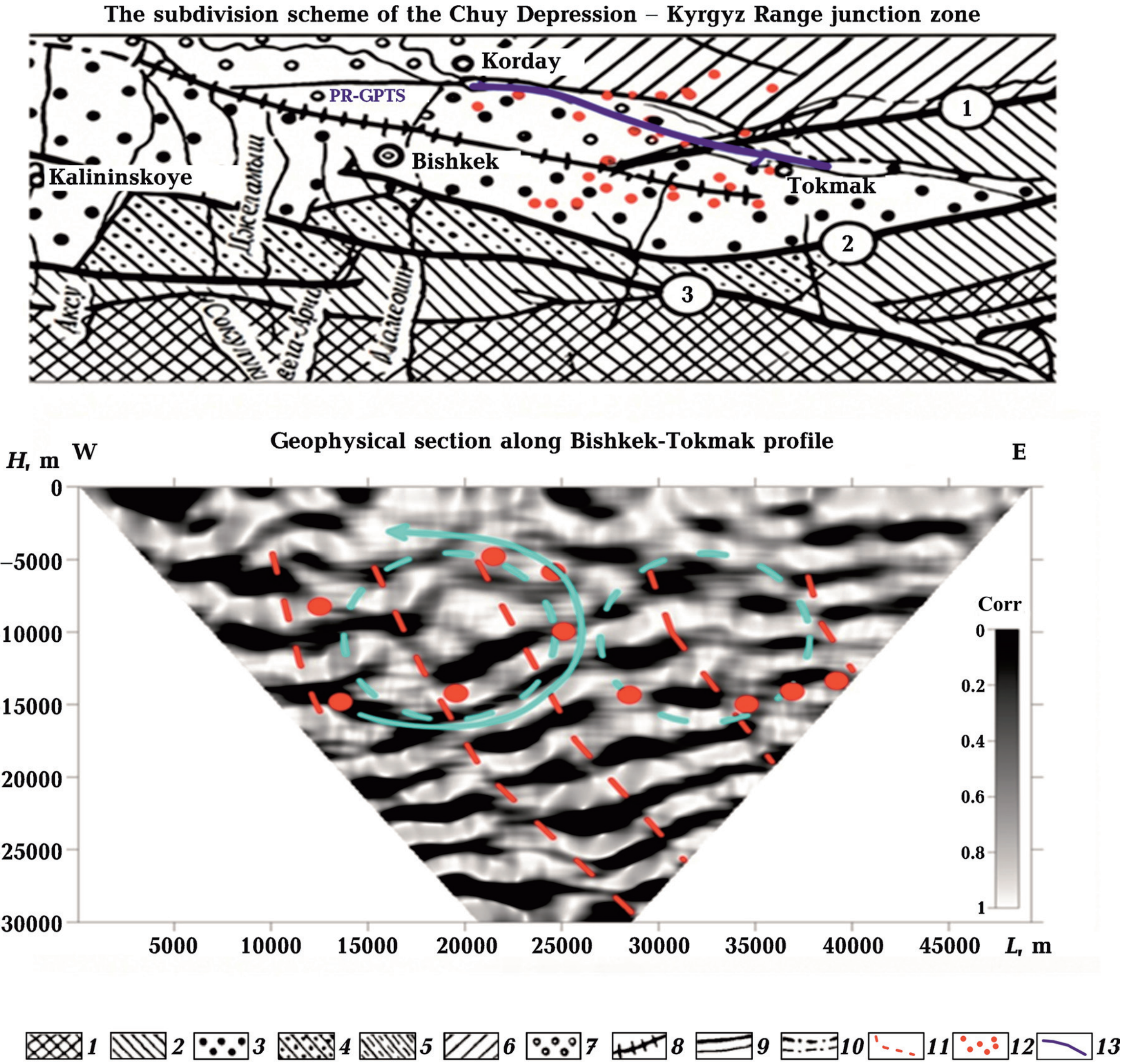

Fig. 2. Tomographic model (GPTS) along the Bishkek-Tokmak profile: *1*, *2* — areas of persistent uplift (up to 4—5 km) during the Cenozoic, beginning in the Oligocene (*1*) and in the Pliocene (*2*); *3* — areas of persistent Cenozoic subsidence (Kyrgyz Trough); *4* — newly formed uplifts within the former Kyrgyz Trough; *5* — intermontane basins with low-amplitude subsidence followed by uplift; *6* — Quaternary uplifts of moderate amplitude in the Chu-Ili Mountains; *7* — areas of predominant Cenozoic subsidence of up to 0.5—1.0 km (Chu Monocline); *8* — flexure-fault zone; *9* — marginal faults (upper symbol) and other faults (lower symbol); *10* — boundaries of zones without faults; *11* — faults according to GPTS data; *12* — earthquake epicenters and hypocentres; *13* — measurement profile. Blue line — axis of the volumetric stress-accumulation zone. Circled numbers denote major faults: 1 — Karakunuz Fault, 2 — Issyk-Ata Fault, 3 — Shamsi-Tunduk Fault.

est degree of temporal variability. Thus, the 3D diagram (K, FD, $\bar{\varphi}$) provides an ellipsoidal representation of tectonic blocks and their fault zones.

These ellipses are interpreted as state invariants of the fault zone rather than merely statistical approximations, defining the permissible domains of seismic event occurrence. A key observation is that the most energetic earthquakes (M>3.5) are located mainly on the shells (Fig. 4) of parametric ellipsoids.

In Fig. 4, each point corresponds to an earthquake for which the values of the fractal dimension FD_{local} and the average instantaneous phase $\bar{\varphi}_{local}$ are calculated locally — in a window of ±250 counts around the nearest point of the GPTS profile. The ellipses reflect two-dimensional projections of the

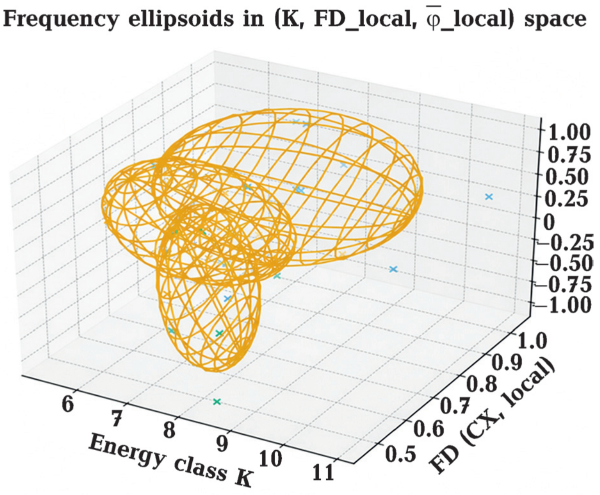
Frequency ellipsoids in (K, FD_local, $\bar{\varphi}$_local) space

Fig. 3. Parametric ellipsoids of seismic event distribution in space (K, FD_{local}, $\bar{\varphi}_{local}$). The markers correspond to individual earthquakes in the catalogue, while the ellipsoids (2σ) approximate the distributions for the western block, the fault zone, and the eastern block. The centers of the ellipsoids reflect the average values of FD_{local} and φ_{local} characteristic of the corresponding geodynamic zones.

covariance ellipsoids of three geodynamic zones: the western block, the fault zone, and the eastern block. The fault is characterized by an increase in FD_{local}, a positive shift in $\bar{\varphi}_{local}$, and a significantly greater spread of data, which is consistent with the increase in dynamical complexity and phase instability of the electromagnetic field in the area of the fault intersection. The blocks on both sides of the fault form compact and distinct ellipses, confirming their structural stability and phase consistency.

Temporal dynamics of the event index. Analysis of λ time series at key points of the profile revealed a characteristic sequence preceding strong seismic events:

– phase of reduced and stable event activity (calm, accumulation);

– phase of increasing λ fluctuations;

– phase of sharp increase in λ, often coinciding with the moment of seismic discharge.

This behavior suggests a connection between the dynamics of λ and phase transitions in the system. In one representative case, 40—60 days prior to an M=4.2 earthquake in the Tokmak node zone, a steady decrease in λ by approximately 25 % relative to the background was observed, followed by a pronounced increase 2—3 days before the event.

Discussion. ***Interpretation of seismic quiescence and the structure of the focal zone.*** These results provide a refined physical interpretation of the phenomenon of seismic quiescence. Within the GPTS framework, quiescence (minimum λ) is an active state with high coherence of collective modes and reduced availability of relaxation channels, which contributes to energy accumulation. This is consistent with volumetric models of seismic foci, where failure is treated as a phase transition in an extended system [Lyakhovsky et al., 1997; Nugraha et al., 2017]. The identified stress cluster is consistent with such a volumetric structure, where discharge occurs at its boundaries rather than in the centre. Thus, GPTS allows distinguishing between passive absence of events and a precursor calm-accumulation state. The interpretation adopted in the present study is also consistent with investigations of spatial-temporal geomagnetic field variations in seismically active regions. In particular, Sobisevich et al. [2014] and Orlyuk et al. [2017] demonstrated that both high-frequency geomagnetic disturbances and long-term variations of the geomagnetic field may correlate with seismic processes and lithospheric magnetic heterogeneity. These results support the idea that stress-controlled structural and magnetic inhomogeneities of the lithosphere can modulate the electromagnetic field and produce diagnostically meaningful variations. In this context, GPTS does not contradict existing geomagnetic observations but provides an event-statistical framework for analyzing such responses in fault-controlled environments.

Event index λ and nonlinearity of the state level. The relationship between λ and the stress-strain state is fundamentally nonlinear. Minimal λ values correspond to maximum accumulated energy. This can be explained by introducing the concept of state-level nonlinearity (in addition to physical, geometric, and structural nonlinearity [Shuman, 2015]). This type of nonlinearity is related to the dynamics of the spectrum of available hybrid

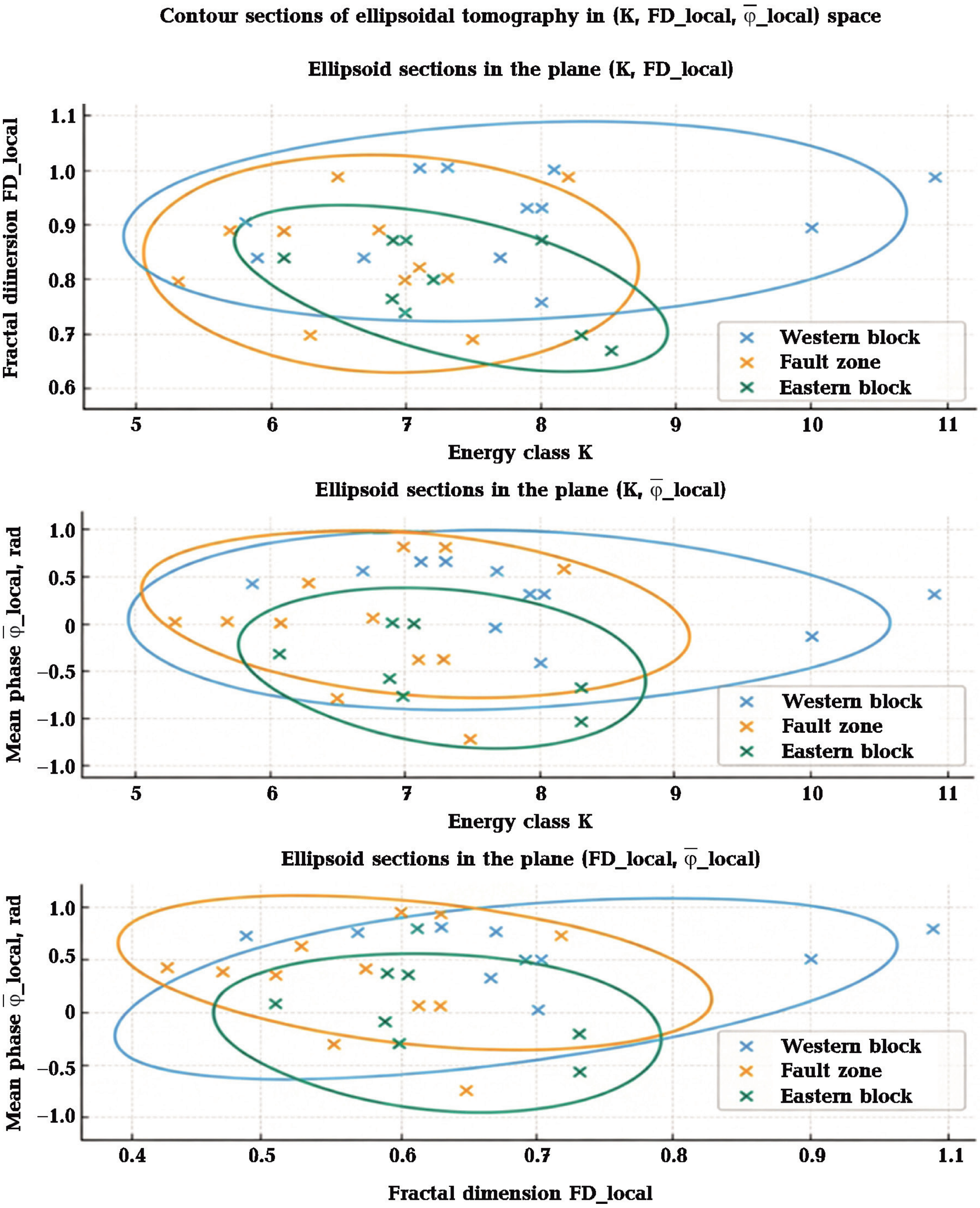

Fig. 4. Parametric ellipses of hypocenters for segments of the fault zone. Cross-sections of ellipsoids and the position of hypocenters relative to their shells are shown.

states of the system: as stresses increase, the spectrum reorganizes, the number of effective relaxation channels decreases, and coherence increases, which is recorded by a decrease in λ. This approach explains the high sensitivity of λ to pre-critical states rather than peak release events.

Although the GPTS method in this work is formalized through the event index λ, which reflects the intensity of transitions between coupled electromagnetic-mechanical states of the geosphere, it is important to emphasize that λ is an integral characteristic of the more complex internal dynamics of the electromagnetic field of the geosphere. This behavior manifests, in particular, in changes in the local fractal dimension of the signal and the phase organization of its components. Parametric ellipsoids reflect the state invariants of fault zones. Analysis of the fractal dimension (FD_{local}) and average instantaneous phase ($\bar{j}_{local}$) shows that the fault is characterized by an expansion of the phase volume, an increase in chaos and phase instability, which in the integral description is recorded by an increase in the event index λ. By contrast, zones with reduced λ (seismic quiescence) correspond to states of increased field coherence, narrowing of the state spectrum, reduction in fractal dimension, and phase stabilization, indicating the accumulation of elastic energy.

Thus, λ is a reduced functional of the fractal-phase structure of the geopolariton response, integrating the microdynamics of the field into event statistics. Fractal-phase parameters do not contradict the use of λ, but constitute its physical basis, providing a multi-level description of the system. Parametric ellipsoids, identified in λ-space and associated with the distribution of hypocenters, reflect the state invariants of fault zones, while fractal and phase characteristics determine the internal geometry of these invariants.

Comparison with V.M. Shuman's model and the position of GPTS. The presented model is conceptually close to the works of V.M. Shuman and other authors who emphasize the role of microstructural heterogeneity, dispersion, and nonlinearity in the generation of geoelectromagnetic signals [Shuman, 2008, 2015; Potirakis et al., 2014]. GPTS shares these physical premises but provides an alternative interpretative framework addressing the skin-depth limitation. While in the classical model the direct propagation of electromagnetic waves from depth is impossible, the geopolariton concept suggests a different mechanism of depth-surface coupling — the cascading transmission of coherent hybrid electromagnetic-mechanical states. This transmission does not involve direct wave energy transfer, but is realized as a hierarchical restructuring of coupled electromagnetic-mechanical states at different scale levels of the lithosphere. Fault zones and fluid channels act not as classical waveguides but as areas of enhanced coupling and state selection, ensuring the stability of correlation transfer. This mechanism enables surface observations to be interpreted consistently with deep stress accumulation processes within the framework of classical electrodynamics. The GPTS method does not record signal transmission from depth, but rather a near-surface event response, the form and statistics of which are determined by the deep state of the geosphere. Cascade transmission manifests as stable correlation scales and spatial consistency of events along the profile, which are used to reconstruct the geometry of deep structures.

Limitations of the method and directions for development. Like any method, GPTS has limitations.

- The effective nature of the model. The strict microphysical relationship between the model parameters (D(ω), Γ(ω)) and the specific properties of rocks requires further theoretical and experimental study.
- Data requirements. The method is based on statistics, which requires the accumulation of sufficient data volumes for reliable estimates. In areas of low activity or with short observation times, the resolution decreases.
- Spatial ambiguity. Similar λ values can occur with different combinations of structural and dynamic parameters. The ambiguity can be reduced by analyzing not just one λ parameter, but a set of invariants (ellipse shape, temporal dynamics).
- Influence of interference. As a passive electromagnetic method, GPTS is susceptible to man-made noise. It is necessary to improve algorithms for identifying events associated specifically with geodynamic processes.

The prospects for the development of the method are linked to the refinement of the physical model based on laboratory experiments, the expansion of the monitoring network and, most importantly, integration with other geophysical data (seismicity, geodesy, radon surveying, and geomagnetic field variations). Future studies will include comparison of the event index λ with geomagnetic field variations and low-frequency magnetic disturbances in order to better constrain the relationship between lithospheric stress processes and regional electromagnetic dynamics.

A comprehensive approach will allow verification of the interpretation and increase the reliability of diagnosing pre-critical states. Of particular interest is the monitoring of regions with predicted high seismicity, such as the Himalayan front or subduction zones.

Conclusion.

- A concept and methodology for passive geopolariton tomography (GPTS) has been developed based on the analysis of event statistics of natural electromagnetic responses. The key parameter of the method is the event index λ, which reflects the intensity of transitions between coupled electromagnetic-mechanical (geopolariton) states of the medium.
- Within the geopolariton framework, the classical skin-depth limitation is reinterpreted at the level of system description. The proposed approach considers near-surface electromagnetic responses as manifestations of cascading reorganization of coupled electromagnetic–mechanical states within fault-controlled domains rather than as direct electromagnetic energy transfer from depth. This interpretation provides a framework for interpreting the observed sensitivity of the method to deep processes in a manner consistent with electromagnetic field propagation in conductive media.
- Application of the GPTS method to the seismically active Bishkek-Tokmak profile (Northern Tien Shan) demonstrates the possibility of identifying volumetric stress clusters. The cores of these clusters are characterized by minimal λ values and are interpreted as dynamically active seismic quiescence zones associated with energy accumulation and increased coherence. A clear spatial relationship between these clusters, regional faults, and the seismofocal zone is observed.
- Earthquake hypocenters in GPTS parameter space form stable ellipsoids that may represent state invariants of fault zones. The localization of the most energetic events near the boundaries of these ellipsoids is consistent with a phase-transition model at the margins of volumetric stress concentrations, providing new opportunities for analyzing the spatial structure of seismogenesis.
- GPTS is positioned as an additional tool for diagnosing pre-critical states and monitoring fault-zone dynamics, complementing conventional seismic and electromagnetic approaches. Its principal advantage lies in its sensitivity to energy accumulation processes rather than post-release signals. Further development of the method will involve its integration into comprehensive geophysical monitoring systems for seismic risk assessment in active tectonic regions.

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Геополяритонна томографія внутрішньої структури Землі: пасивний метод аналізу сейсмогенних зон

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У цьому дослідженні представлено геополяритонну томографію — пасивний геофізичний метод для вивчення динамічних станів літосфери на основі статистики подій природних електромагнітних реакцій. На відміну від традиційних електромагнітних і сейсмічних підходів, геополяритонна томографія не базується на частотному чи амплітудному аналізі, а використовує індекс подій λ, що відображає інтенсивність переходів між зв'язаними електромагнітно-механічними станами геосфери. Дослідження вводить геополяритонні стани як зв'язані електромагнітно-механічні відповіді, у яких енергія розподіляється між електромагнітним і еластичним режимами релаксації. У цій рамці класичне обмеження глибини скін-шару розглядається на рівні опису системи: спостережувані ефекти інтерпретуються як напруго-контрольована модуляція та каскадна реорганізація зв'язаних станів, локалізована переважно в структурах, контрольованих несправністю, а не як пряме електромагнітне проникнення з глибини. Використовуючи профіль Бішкек—Токмак (Північний Тянь-Шань) як кейс-стаді, метод виявляє об'ємні кластери напружень і зони сейсмічного спокою, які інтерпретуються як динамічно активні режими накопичення еластичної енергії. Гіпоцентри землетрусів утворюють стабільні параметричні еліпсоїди, при цьому найенергійніші події зосереджені поблизу їхніх меж, що відповідає процесам, схожим на фазовий перехід, між накопиченням енергії та вивільненням. Обговорюється фізичне значення індексу події λ та його нелінійний зв'язок із станом напруження—деформації літосфери. Геополяритонна томографія позиціонується як інструмент для діагностики передкритичних станів і моніторингу динаміки зон розломів, а не для детермінованого прогнозування землетрусів.

Ключові слова: геополяритонна томографія, пасивні геофізичні методи, подієвий індекс λ, кореляційна томографія, сейсмогенні зони, напружено-деформований стан.