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The Geological Pathway Diversity Model (GPDM)

A Multi-Site Framework for Atmospheric Plasma Phenomena

Version 2.5 | June 2026

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Version 2.5 — Adversarial Self-Review Revision

This version supersedes v2.4 (April 2026). Following publication, the authors conducted a systematic adversarial self-review, submitting specific claims to independent multi-model critique with instruction to attack from the strongest available disciplinary angle. Four peripheral elements were identified as not meeting the evidentiary standard of the core framework and have been removed:

1. **Skinwalker Ranch** replaced with **Uinta Basin Candidate Zone** — the named private property is inaccessible to independent monitoring deployment (the GPDM's own falsification protocol requires independent access); the basin-scale geology is sound and justified here on USGS stratigraphy alone.

2. **Mt. Kholat Syakhl / Dyatlov Pass (1959) removed** — primary source (Kuersten 2021) is self-published and not peer-reviewed; radiation evidence is contested and was not acknowledged as such; injury mechanisms have multiple documented competing explanations that were not excluded.

3. **Section 11a (mycorrhizal networks and tree bioelectric generation) removed from primary framework** — cited laboratory sources do not demonstrate geological-scale telluric current propagation; network resistance is 390–19,600× higher than surrounding soil matrix; charge storage capacity is quantitatively insufficient by several orders of magnitude for plasma discharge contribution.

4. **NUFORC database removed** — self-reported, unverified anecdotal data; the spatial correlation analysis was cited as a conclusion before it was performed; no controls for population density, military aviation, or media feedback were applied.

The core framework — Freund p-hole mechanism, four-variable state equation, Pathways 1–6, Hessdalen and Brown Mountain validation, null-site falsification protocol — is unchanged. Every removal was a late addition grafted onto a sound core. The core survived adversarial review intact.

Abstract

Atmospheric plasma phenomena — persistent luminous orbs, recurrent earth lights, and earthquake lights — observed at geographically distributed sites worldwide have historically resisted unified physical explanation.

The Geological Pathway Diversity Model (GPDM) proposes that these phenomena share a common mechanism family rooted in stress-activated electronic charge carrier physics, with site-specific expression determined by local lithology, fault geometry, tectonic stress regime, and atmospheric state. Six geological activation pathways are formally classified: (1) p-hole/peroxy charge carrier activation in mafic igneous rocks (Freund mechanism); (2) textural piezoelectric emission in crystallographically aligned quartz-bearing metamorphic and hydrothermal vein rocks; (3) triboelectric/microcracking broadband EMR from brittle fracture; (4) electrochemical/atmospheric plasma confinement driven by natural galvanic battery geometry; (5) radon/alpha-ionization dusty plasma formation; (6) seismoelectric/hydroelectric coupling in water-saturated fault zone geology. A four-variable state equation governs output intensity and type across all pathways. Three primary field sites — Brown Mountain (North Carolina), Hessdalen Valley (Norway), and La Peña de Juaica (Colombia) — anchor the multi-continent comparative framework. The model generates testable predictions including a tidal predictive calendar, GIS spatial methodology for new site identification, and a null-site falsification protocol. Deployment of a standardized monitoring package (ULF magnetometer, air ion counter, IR thermal camera, electric field meter, calibrated color camera) at geologically qualified sites is proposed as the primary validation pathway.

Keywords: atmospheric plasma phenomena; geological plasma discharge; p-hole charge carriers; Freund mechanism; earthquake lights; earth lights; Hessdalen; Brown Mountain; fault zone geophysics; electrokinetic streaming; seismoelectric effect; tidal modulation; multi-site framework; Presignal Research Initiative

1. Introduction

Seismic waves are the most studied expression of tectonic stress in the Earth's crust. They are not, however, the only one. A parallel body of observation — documented across centuries, from multiple continents, by investigators ranging from field naturalists to astrophysicists — records luminous phenomena that appear at persistent geographic locations, often in correlation with geological and atmospheric conditions rather than with discrete seismic events.

These phenomena present in two primary modes. The first is co-seismic: brief, intense flashes of light appearing at the Earth's surface immediately before, during, or after earthquake rupture — earthquake lights (EQLs) documented photographically during the Matsushiro swarm (Japan, 1965–67), the Saguenay event (Quebec, 1988), and the Kobe earthquake (Japan, 1995), among many others. The second is sustained: long-duration luminous plasma orbs recurring at specific valley and ridge locations over decades, most systematically documented at Hessdalen, Norway, since 1984.

Until recently these two modes were treated as distinct phenomena requiring separate explanations. The discovery by Freund and colleagues (2002–2019) that essentially all igneous and high-grade metamorphic crustal rock contains dormant positive hole (p-hole) charge carriers — defect electrons in the oxygen anion sublattice, released by mechanical stress — provides a unifying physical substrate. When p-holes are activated in sufficient numbers, they propagate through unstressed rock at 200–300 m/sec via phonon-assisted electron hopping, accumulate at the Earth's surface, field-ionize atmospheric oxygen, and produce corona discharges accompanied by visible light emission, ULF electromagnetic pulses, infrared radiation, and air ionization cascades.

The Geological Pathway Diversity Model (GPDM) extends this foundation by proposing that the specific expression of atmospheric plasma phenomena at any given site is determined by a combination of geological activation pathway, local lithology, tectonic geometry, and environmental state variables. Different sites activate different dominant pathways or combinations thereof — producing the observed diversity of phenomenological expression from a shared physical substrate.

The model's core claim is that recurrent earth lights sites are not geologically arbitrary. They represent locations where geological conditions favor sustained charge carrier activation at sub-rupture stress levels, producing long-duration plasma phenomena rather than the brief co-seismic discharge associated with fault rupture. The same underlying physics operates at both ends of the expression spectrum.

2. Theoretical Foundation: The P-hole Mechanism

2.1 Peroxy Defects and Dormant Charge Carriers

Silicate minerals crystallizing from H₂O-laden magmas incorporate small amounts of water as hydroxyl pairs (OH⁻). During cooling through the 600–400°C window, hydroxyl pairs undergo a redox conversion in which protons steal electrons from adjacent oxygen anions, forming H₂ gas while the oxygens are oxidized from O²⁻ to O⁻, creating peroxy links of the form O₃Si-OO-SiO₃. These peroxy links — positive hole pairs (PHPs) — are electrically inactive in their bound state but constitute latent charge carrier capacity throughout the rock.

Freund (2010) established that peroxy defects are ubiquitous in the mineral world: every igneous and high-grade metamorphic rock in the Earth's crust carries a non-zero complement of peroxy links, as does every sedimentary rock containing detrital mineral grains from igneous and metamorphic sources. This universality is fundamental to the GPDM's multi-site applicability — the geological substrate for p-hole activation is not restricted to exotic rock types but is present wherever crystalline rock exists.

2.2 Stress Activation and Charge Carrier Propagation

When rocks are subjected to deviatoric stress, dislocations sweep through mineral grains. Each time a dislocation intersects a peroxy link, it momentarily breaks the O⁻-O⁻ bond, releasing a mobile positive hole (h^{*}). The stressed rock volume turns into a battery: h^{*} charge carriers flow laterally into unstressed rock while electrons flow downward toward the n-type conducting lower crust.

The boundary between stressed and unstressed rock acts as a Schottky barrier — passing h^{*} carriers but blocking electrons. This rectifying behavior produces the unipolar magnetic pulse signature documented by Bleier et al. (2009, 2013) at the Alum Rock and Tacna earthquake preparation zones. P-holes propagate at 200–300 m/sec via phonon-assisted electron hopping — a propagation speed confirmed in laboratory impact experiments and field measurements of the 8-second pulse arrival offset between two magnetometer stations 1 km apart at Alum Rock.

2.3 Surface Arrival and Atmospheric Coupling

When h^{*} charge clouds reach the Earth's surface, they accumulate in a thin subsurface charge layer. The associated electric field reaches 400,000 V/cm at a flat surface and significantly higher at topographic convex points — edges, ridges, and mountain peaks. This field exceeds the ionization threshold of air, producing field ionization of O₂ molecules followed by corona discharge onset. Each corona discharge produces a flash of visible light, a burst of RF emission in the kHz range, and a brief reversal of surface polarity — after which h^{*} influx from the bulk replenishes the charge, creating rapid-fire discharge sequences.

Two operating modes are distinguished. In *battery mode* — the dominant mode at non-seismic recurrent earth lights sites — sustained sub-threshold h^{*} outflow produces continuous low-amplitude signals (ULF pulses, air ionization, IR emission) over timescales of hours to months. In *plasma burst mode* — operative at earthquake preparation zones approaching rupture — p-hole concentration exceeds a critical threshold, forming a degenerate solid-state plasma that bursts outward explosively, producing co-seismic EQL flashes of the type documented at Saguenay (St-Laurent, Derr & Freund 2006) and Kobe (Tsukuda 1997).

3. The Six-Pathway Classification System

The GPDM classifies atmospheric plasma phenomena at recurrent sites into six geological activation pathways. Each pathway reflects a distinct primary mechanism of charge carrier generation or plasma formation, though pathways frequently co-occur. The OR logic structure is critical: the four-variable state equation operates as a parallel system — a single pathway achieving threshold activation is sufficient to produce observable output.

Pathway	Mechanism	Host Geology	Key Output	Primary Sites
1 — P-hole / Peroxy (Freund)	Dislocation-activated peroxy link dissociation releasing mobile h* carriers	Mafic igneous (gabbro, basalt, granite); H ₂ O-laden magmatic crystallization	Pre-seismic ULF magnetic pulses; positive ion emission; corona discharge; co-seismic EQL flash; IR anomaly	Saguenay QC 1988; Kobe 1995; Alum Rock 2007; Lima 2007
2 — Textural Piezoelectric	Stress on polar-axis-aligned quartz lattice; Dauphine- twinned quartzite under shear	Vein quartz in fault zones; High-grade metamorphic quartzite (LPO + polarity alignment required)	Net surface EM field; plasma initiation; broadband EM 8–40 kHz	Kaikoura NZ 2016; Hessdalen (vein quartz); Brown Mountain NC (predicted)
3 — Triboelectric / Microcracking	Brittle fracture stress-drop events; grain boundary friction	Any brittle quartz-bearing rock; texturally aligned metamorphic quartzite	Broadband EMR <40 kHz; directional radiation; correlated acoustic emission	Obir Cave fault, Alps; Galena Mine quartzite ID; Edgar Mine CO
4 — Electrochemical / Atmospheric (Natural Battery)	Galvanic potential across electrochemically differentiated mineral deposits; groundwater ionic transport circuit closure	Sulfide mineral deposits (oxidation/reduction couples) separated by fault geometry with conductive groundwater	Long-duration thermally self-regulating plasma orbs; clustering effect; VLF Doppler; IR + radar signatures	Hessdalen, Norway (primary — iron/zinc/copper battery confirmed VLF); Marfa TX (spectroscopic)
5 — Radon / Alpha-Ionization (Dusty Plasma)	Radon-222 decay alpha particles -> air/dust ionization ~10 ⁵ ion pairs/cm ³	U/Th-bearing rock in fault zones with radon emanation pathways; sulfide minerals with radioactive trace elements	Coulomb crystal cluster formations; long-duration luminous plasmoids; helium spectral signature	Hessdalen (He spectral signature detected); Kobe precursor zone (10x radon spike)
6 — Seismoelectric / Hydroelectric (v2.3)	Acoustic stress waves through water-saturated porous rock; ionic groundwater streaming potentials -> EM emission	Water-saturated fractured fault zones; ionic groundwater in porous capillaries; freshwater- saltwater interfaces	Oscillating EM field at surface; groundwater EC anomaly (days–60 days pre-event); streaming potential voltage	Hessdalen (sulfide aquifer + lakes — Pathway 4+6 superposition); Brown Mountain NC; Taro Valley Italy

Note on Hessdalen Pathway Assignment: Vargemezis et al. (2024) confirmed that Hessdalen valley seismicity has not exceeded M2.5 since 2000, explicitly ruling out Freund's seismic stress trigger (Pathway 1) as the primary active mechanism. The gabbro substrate is present (PHP-bearing), but the stress trigger is insufficient. Pathway 4 (natural battery, confirmed by VLF survey and EFM measurements) is the primary active mechanism. This finding strengthens the GPDM by demonstrating that Variable 1 (stress rate) can be near-zero while the system remains active through Pathway 4's electrochemical circuit — confirming the OR logic structure of the state equation.

4. The Four-Variable State Equation

The GPDM's output intensity and type at any given site and moment is governed by four primary variables. The equation operates with OR logic across pathways and has a branching structure at Variable 3:

$$\Phi(\text{output}) = f(V1, V2, V3, V4)$$

Variable 1 — Stress Rate (d σ /dt)

Controls the rate of dislocation generation and therefore the rate of PHP dissociation and h* production. Stress input sources include tectonic loading (primary for co-seismic EQL), S-wave shear passage (documented trigger, Freund 2019), tidal loading (Baron et al. 2022 confirm tidal ground surface displacement of up to 10 cm at monitoring sites), and microseismic background from distant ocean wave interactions (Bromirski 2001). Critical finding from Freund (2010): p-hole carriers persist for days to months under sustained constant stress, with three distinct carrier lifetime populations. Variable 1 can be near-zero at Hessdalen while Pathway 4 continues operating — confirming OR logic.

Variable 2 — Carrier Density / Lithology (rho_PHP)

The PHP concentration in the geological substrate, which is a function of rock type and crystallization history. Highest in mafic igneous rocks (gabbro, basalt) crystallized from H₂O-laden magmas at depth. For Pathway 2, Variable 2 encompasses both quartz content and the presence of oriented electric axis polarity — lattice preferred orientation alone is insufficient; polarity orientation is required for net macroscopic piezoelectric field emergence.

Variable 3 — Atmospheric / Environmental State (Psi_atm)

The bifurcation variable. Controls the output type given that charge carriers have reached the surface. High humidity (80–90%, documented at Hessdalen during events by Teodorani 2004) enables electrochemical confinement, producing sustained plasma orbs (Pathway 4 output). Low humidity or high topographic relief favors corona discharge and EQL flash (Pathway 1/2 output). Natural gas seeping through fault zone geology modifies the atmospheric chemistry at discharge points, changing which molecules ionize first and extending the APP color-as-geological-indicator diagnostic to include gas composition as a readable variable (active at Taro Valley, Italy).

Variable 4 — Geometric Confinement and Circuit Closure Pathway

The structural geometry of the charge carrier activation volume and its surface emergence pathway. Includes: dyke and fault orientation relative to stress field; topographic geometry at emergence point; and circuit closure mechanism — three natural pathways identified by Freund (2010): (i) downward electron flow to the n-type conducting lower crust; (ii) electrolytic circuit closure through saline groundwater; (iii) atmospheric circuit closure via massive air ionization. The Hessdalen natural battery geometry (Monari et al. 2013, Vargemezis et al. 2024) is a specific expression of Variable 4 in which the electrochemical potential difference between spatially separated mineral deposits drives a circuit with groundwater as the electrolyte.

5. Primary Field Sites and Candidate Zones

The following sites anchor the GPDM's comparative multi-site framework. Each has independent documentation of recurrent atmospheric plasma phenomena, geological characterization assigning it to one or more GPDM pathways, and an active or pending research relationship supporting future monitoring deployment. All candidate zone justifications are based on published geological survey data and peer-reviewed geophysical literature.

Site	Geology	Phenomena	Active Pathways	Status
Brown Mountain, NC, USA	Appalachian fold-thrust belt; metamorphic quartzite with Deformation texture (Leydolt/Dauphine twinning); hydrothermal vein quartz in fault zones; mixed PHP-bearing metamorphic rock. Almost completely encircled by thrust faults (Bryant & Reed, USGS Professional Paper 615).	Recurrent luminous orbs documented since 19th century. L.E.M.U.R. (2004) independently documented: Geiger ionization anomalies; erratic telluric ground currents millivolts to >1V; VLF anomalies at ~140 kHz; Kp >= 5 correlation; rain correlation; thrust fault encirclement. All 10 major L.E.M.U.R. findings map directly onto GPDM pathway predictions.	1 (primary), 2 (textured quartzite), 3 (microcracking), 5 (radon — Geiger anomalies documented)	Primary GPDM field site. L.E.M.U.R. 2004 report formally cited as independent field validation dataset. Active research collaboration with Warren / L.E.M.U.R. team pending.
Hessdalen Valley, Norway	Gabbro and amphibolite formations (PHP-bearing, Freund mechanism substrate); quartz-rich mica schists; sulfide mineral deposits (iron/zinc west, copper east); VLF-confirmed conductive zones tracing 6x12 km ellipse of gabbro intrusion.	Most instrumented earth lights site on Earth. 40 years of documented data. Key anomalies: flat-topped steep-sided luminosity distribution; thermally self-regulated plasma orbs; clustering effect; VLF Doppler signals; radar tracks. Radiant power up to 19 kW in cluster events. Helium spectral signature (Pathway 5).	4 (primary — natural battery confirmed Vargemezis et al. 2024); 1 (substrate present, seismicity below M2.5); 2 (vein quartz); 5 (radon/dusty plasma)	Active collaboration. GPDM v2.5 sent to Fred Pallesen (CEO, Project Hessdalen). Introductions made to Daniel Nordvik and Henning Kuersten via Fred.
La Peña de Juaiça, Colombia	Andean setting; geological characterization in development.	Recurrent atmospheric lights documented. Southern hemisphere anchor site for multi-continent comparison.	To be determined pending geological literature	Framework anchor site. Geological literature search in progress.
Taro Valley (Val di Taro), Italy	Northern Apennines fold-thrust belt; TAL and LEF boundary fault systems; Plio-Quaternary sedimentary basin overlying Messinian deposits; high natural gas field density (48% of Italy's gas extraction from this province).	750+ ball lightning and APP reports documented since 1900 in Emilia-Romagna province. Events concentrated along fault systems and near oil/gas infrastructure. Straser documented direct field observation of APP emerging from clayey soil in a ravine along the Taro Valley Seismic Line.	1 (primary — p-hole in Apennine thrust fault); 3 (triboelectric); Variable 3 — natural gas atmospheric ionization modifier	GPDM candidate site (v2.2). High natural gas density creates unique Variable 3 conditions.

Site	Geology	Phenomena	Active Pathways	Status
Southern California Fault Zones, USA	San Andreas Fault system (right-lateral strike-slip, ~1300 km); Garlock Fault (left-lateral); Elsinore; San Jacinto; Newport-Inglewood-Rose Canyon. Predominant lithology: granitic and metamorphic basement (Peninsular Ranges Batholith) with extensive mafic intrusions. High PHP density substrate confirmed by USGS geological survey mapping.	Active seismic fault corridors with documented earthquake light events associated with major ruptures in the historical record. Geological conditions — high PHP substrate, active strike-slip faulting, mafic basement — satisfy Pathways 1, 2, and 3 criteria directly.	1 (primary — p-hole in granitic/mafic basement along active strike-slip faults); 2 (textural piezoelectric — Peninsular Ranges metamorphic basement); 3 (triboelectric — high microseismic background)	GPDM candidate zone. Geological justification based on USGS fault mapping, Peninsular Ranges Batholith stratigraphy, and documented EQL events in historical record.
Uinta Basin Candidate Zone, Utah, USA	Uinta Basin — Eocene sedimentary basin overlying Precambrian quartzite basement (Uinta Mountains to north; high PHP potential per Freund universality). Significant oil and gas production with associated hydrocarbon geology. Sedimentary-basement interface conditions consistent with Variable 4 circuit closure. Documented geomagnetic anomalies in the region.	Regional geological conditions — Precambrian quartzite basement, sedimentary-basement interface, hydrocarbon geology, and freshwater-brine groundwater interfaces — satisfy Pathway 1, 4, and 6 criteria. Candidate monitoring sites to be selected based on accessibility and independent deployment requirements.	1 (p-hole — Precambrian quartzite basement); 4 (electrochemical — sedimentary basin/basement interface); 6 (groundwater electrokinetic streaming)	GPDM candidate zone (v2.5). Justification based on USGS stratigraphic mapping and regional geophysical surveys. Monitoring site selection pending independent access assessment.

6. The Tidal Predictive Calendar

The GPDM's tidal predictive calendar is grounded in the confirmed relationship between tidal loading and rock strain at monitoring sites. Baron et al. (2022) documented tidal ground surface displacement of up to 10 cm vertical at the Obir Cave fault monitoring site, establishing that tidal loading cycles produce measurable strain changes at geologically active sites.

The critical revision from Freund (2010) is that the tidal calendar does not predict discrete activation events — it predicts output intensity modulation of an already-active system. P-hole carriers persist for days to months under sustained tectonic stress. Tidal loading cycles therefore modulate the surface-arriving h^* flux rather than switching carrier generation on and off. The calendar predicts: enhanced corona discharge probability during tidal stress maxima; suppressed output during tidal unloading phases; and compounded enhancement during coincident tidal stress maxima and elevated regional seismicity.

Specific tidal predictions for Brown Mountain and Hessdalen require site-specific tidal loading models incorporating both solid earth tides and microseismic background from ocean wave activity (Bromirski 2001). This is identified as a primary next development step for GPDM v3. Lunar and planetary tidal contributions are incorporated into the Variable 1 modulation framework: the NEO-6M GPS module in the field node provides

precise UTC timestamps, enabling automated tidal phase correlation against every sensor reading as a software addition to the logging pipeline.

7. GIS Spatial Prediction Methodology

The GPDM's GIS spatial prediction methodology maps the geological conditions required for each pathway to identify high-probability new sites where atmospheric plasma phenomena should occur but have not yet been systematically documented. All site identification is based on published geological survey data, peer-reviewed geophysical literature, and direct geological mapping — not on self-reported sighting databases.

The primary mapping layers are: (1) mafic igneous and high-grade metamorphic rock distribution (Pathway 1 substrate); (2) fault zone vein quartz and metamorphic quartzite with deformation texture (Pathway 2 substrate); (3) electrochemically differentiated mineral deposit pairs separated by fault geometry with groundwater connectivity (Pathway 4 substrate); (4) uranium/thorium-bearing rock in fault zones with documented radon emanation (Pathway 5 substrate); (5) water-saturated fractured fault zones with ionic groundwater in porous capillaries (Pathway 6 substrate).

The Vargemezis et al. (2024) conclusion explicitly invites this methodology: 'The particular geological structure detected in Hessdalen valley may encourage similar campaigns in other areas where similar phenomena are observed.' The GPDM formalizes the geological selection criteria that would guide such campaigns. Two forward site predictions have been made under the GPDM framework based on this methodology and will be formally documented in a companion technical note prior to field verification.

8. Null-Site Falsification Protocol

A scientific framework that cannot be falsified is not science. The GPDM's null-site falsification protocol defines the conditions under which the framework's predictions are demonstrably wrong.

The protocol identifies geologically equivalent sites — matching the lithology, fault geometry, tectonic stress regime, and atmospheric conditions of confirmed GPDM sites — where no atmospheric plasma phenomena have been documented. If the GPDM's pathway conditions are both necessary and sufficient predictors of phenomena, null sites should either: (a) lack one or more required pathway variables; or (b) represent sites where phenomena occur but have not been reported due to low population density or observer access.

Protocol design: Select five candidate null sites matched to Brown Mountain's Appalachian quartzite geology. Assess each against the four-variable state equation. Predict which should show phenomena (positive prediction) and which should not (null prediction). Deploy the standard monitoring package at all five for a minimum 12-month period. If positive-predicted sites show no signal and null-predicted sites show signal, the framework is falsified. If results match predictions, the framework is strengthened. All null-site deployments must be independently executed at publicly accessible locations — independent access is a prerequisite, not a preference.

9. APP Color as Geological Indicator

A novel diagnostic tool emerges from the integration of APP spectroscopic data with the GPDM's geological framework. The observed color of an atmospheric plasma phenomenon is a direct spectral readout of the elemental composition being ionized at the discharge point — identical in principle to the color differentiation of meteors by mineral composition.

APP color is therefore not random. It is diagnostic of the local mineral chemistry at the discharge point. This reframes the entire historical sighting record: every historical APP report that includes a color description is a

low-resolution spectral reading of the local geology.

9.1 Predicted Color-Geology Correlations

White to yellow-white: Silicon, iron, scandium ionization. Consistent with mixed metamorphic and gabbro geology. Matches Hessdalen documented spectrum (Teodorani 2004; Boccippio et al. 2002 spectral analysis confirming silicon, iron, scandium in Hessdalen lights).

Orange to red: Iron oxide compounds dominant. Consistent with iron-rich metamorphic geology. Predicted dominant color at Brown Mountain (Appalachian iron-bearing quartzite substrate).

Blue to blue-green: Ionized nitrogen dominant (atmospheric) or copper compounds (geological). Blue-green at copper-bearing geological sites — consistent with copper deposits on the eastern side of Hessdalen valley and the documented occasional blue-green Hessdalen events.

Yellow to yellow-green: Sulfur compounds dominant. Consistent with sulfide mineral geology — Pathway 4 electrochemical battery substrate (iron/zinc sulfides). Yellow-green events at Hessdalen are predicted to correlate with western valley (sulfide-rich) discharge points.

Violet to purple: Ionized nitrogen in dense plasma (spectral N_2^+ emission). Consistent with high-energy plasma burst mode events.

9.2 Implications for Historical Record Reanalysis

This diagnostic framework opens a new research pathway: systematic color coding of the historical APP sighting record against geological substrate maps. Sites with copper-bearing geology should show statistically higher rates of blue-green APP reports. Iron-rich sites should show higher rates of orange-red reports. This is testable against existing datasets — Project Hessdalen AMS color data, the M-Zone photographic record, and the L.E.M.U.R. Brown Mountain video archive.

10. Pathway 6 — Seismoelectric and Hydroelectric Coupling

10.1 The Seismoelectric Effect

When an acoustic stress wave propagates through water-saturated porous rock, it induces relative motion between the rock matrix and the ionic fluid in the pore capillaries. This motion produces streaming potentials — electric dipoles — that radiate detectable electromagnetic fields at the surface. This is the seismoelectric effect, documented since Thompson and Gist (1993) detected seismoelectric waves from a gas-water interface at 300 meter depth.

The critical GPDM insight is that the seismoelectric effect provides a second activation pathway at any site where Pathway 4 (natural battery) or Pathway 1 (p-hole) is already active. The acoustic wave mobilizes existing ionic charge through the aquifer geometry, producing EM emission that adds to and modulates the existing geological discharge mechanism. Water is not merely the electrolyte for Pathway 4 — water is an independent transducer converting mechanical stress into electromagnetic output.

10.2 Groundwater EC Anomaly — The 60-Day Precursor

The most operationally significant finding connected to Pathway 6 is the groundwater electrical conductivity (EC) anomaly documented before seismic events. Iannaccone et al. (2018) identified significant EC anomalies in the Gran Sasso borehole beginning approximately 60 days before the 2016 Amatrice M6.0 earthquake — the longest pre-seismic precursor window documented in the literature for any single measurement channel.

The mechanism (Byerlee 1993): episodic flow of high-pressure water between compartments in the fault zone precedes earthquake occurrence. As pre-seismic stress builds, micro-fractures open, allowing groundwater to migrate between compartments of different ionic concentration. The mixing changes the electrical conductivity of monitored wells and surface water bodies — this conductivity change is both the precursor signal and the Pathway 6 activation indicator.

10.3 The CME–Water Table Chain

A coronal mass ejection arriving at Earth compresses the magnetosphere, producing rapid changes in the global atmospheric electric circuit. The complete chain: CME -> Forbush cosmic ray decrease at Geiger counter (48–96 hours precursor) -> ionospheric TEC anomaly (24–72 hours) -> Kp threshold crossing -> atmospheric electric field coupling to water table -> electrokinetic streaming potential modulation -> Pathway 6 EM emission -> potential APP discharge coincident with Pathway 4 or Pathway 1 activation. Every link in this chain is independently documented in the peer-reviewed literature. The Presignal Field Node monitoring package captures every link simultaneously.

10.4 Monitoring Addition — Water EC Probe

A TDS/EC water conductivity probe deployed in the nearest surface water body or groundwater access point adds the Pathway 6 direct monitoring channel. Continuous logging of water electrical conductivity at 1-minute intervals. A sustained EC anomaly beginning days to weeks before other sensor anomalies is consistent with the pre-seismic groundwater compartment mixing described by Byerlee (1993) and documented by Iannaccone et al. (2018). Where borehole access exists, subsurface EC monitoring is the preferred measurement.

11. Catatumbo — Contrast Case and Variable 3 Clarification

The Catatumbo Lightning phenomenon of Venezuela was initially considered as a potential anchor case for the dry thunderstorm modifier of Variable 3. Formal analysis of Bürgesser, Nicora & Ávila (2012) — the definitive characterization study using WLLN and Lightning Imaging Sensor data — requires a significant reassessment.

Bürgesser et al. (2012) confirm that Catatumbo's semiannual activity pattern correlates with the Caribbean Low-Level Jet (CLLJ) cycle and the Western Hemisphere Warm Pool seasonal expansion. The diurnal cycle peaks between 23:00 and 09:00 local time, driven by nocturnal low-level jet moisture delivery from the Caribbean. The pyroelectrical/methane model is explicitly falsified: it predicts maximum activity during the dry season, which is directly opposite to the observed data.

Catatumbo is therefore a meteorologically driven wet convection system — the most intense persistent thunderstorm on Earth, but fundamentally an atmospheric phenomenon driven by moisture dynamics rather than a geological charge carrier site. It is retained as a contrast case: documenting what pure atmospheric persistent lightning looks like at maximum intensity without geological coupling. Its documented spectral, behavioral, and spatial characteristics provide the baseline against which geologically-modulated APP sites are distinguished.

12. Proposed Monitoring Network

The validation pathway for the GPDM is a standardized multi-instrument monitoring network deployed at geologically qualified sites with independent research access. The instrument package is derived from the QuakeFinder/Freund methodology validated at the Alum Rock M5.4 earthquake (Bleier et al. 2009) and the Bass Lake granite boulder field experiment (Bleier et al. 2013).

Five-Sensor Standard Package: (1) ULF induction magnetometer (0.01–12 Hz, sensitivity ~0.1 pT/sqrtHz at 1 Hz) for unipolar pulse detection; (2) Air ion counter / conductivity sensor for positive and negative airborne ion

monitoring; (3) IR thermal camera (8–12 um) for non-thermal IR emission and night-time cooling slope analysis; (4) Calibrated color camera for APP spectral color documentation — mineral composition diagnostic; (5) Electric Field Meter (EFM) for direct surface electric field measurement — detects p-hole surface charge accumulation before corona discharge threshold.

Optional Enhancements: (6) Geiger counter for Pathway 5 radon/alpha ionization documentation; (7) Radon monitor in groundwater or soil gas; (8) Geophone for acoustic emission correlation; (9) GPS-synchronized timing for multi-site pulse propagation analysis; (10) TDS/EC water conductivity probe for Pathway 6 groundwater monitoring.

ULF Discrimination Layer (Strumik et al. 2021): Lightning generates ULF fluctuations with characteristic bipolar waveform and 0.2–0.5 second time lag from the optical event. Geological p-hole ULF is unipolar (Schottky barrier rectification), duration 1–30 seconds, localized to site. These signatures are sufficiently distinct for real-time discrimination at monitoring sites.

Phase 1 anchor deployments: Brown Mountain, NC; Hessdalen Valley, Norway; one Canadian Shield site within the Western Quebec Seismic Zone. Phase 2: NATO member-state sites (Finland, Italy, Greece, Turkey). One network, one dataset, two government mandates — UAP characterization and NRCan seismic precursor research.

13. Conclusions and Forward Predictions

The Geological Pathway Diversity Model establishes that recurrent atmospheric plasma phenomena at persistent global sites are not geographically arbitrary and not mechanistically diverse. They represent the surface expression of a family of geological charge carrier activation processes sharing a common physical substrate — peroxy defect chemistry in crustal silicate minerals — with site-specific expression determined by local lithology, fault geometry, tectonic stress regime, and atmospheric state.

The framework is novel in connecting non-seismic recurrent earth lights sites to the pre-earthquake signal literature through the shared p-hole mechanism, and in proposing a standardized monitoring methodology generating the first interoperable multi-continent APP dataset.

Forward predictions: (1) Tidal stress maxima will correlate with increased event frequency at Brown Mountain and Hessdalen at statistically significant levels over 24 months. (2) Two GIS forward site predictions will show anomalous phenomena upon monitoring deployment. (3) Null-site protocol will correctly classify at least 4 of 5 candidate sites. (4) APP color distribution at monitoring sites will correlate with local mineral composition at statistically significant levels.

These predictions are falsifiable, instrumentally testable, and grounded in peer-reviewed science. The monitoring network deployment is the next step.

14. Citation Status

The following citations have been verified as part of the GPDM evidence base. Full text has been obtained and analyzed for all citations marked as verified. All citations are from peer-reviewed journals, conference proceedings with editorial review, or primary field datasets.

Citation	Title	Journal / Source	Status
Freund, F.T. (2003)	Rocks That Crackle and Sparkle and Glow	J. Scientific Exploration 17(1): 37-71	Full text verified
Freund, F.T. (2007a)	Pre-earthquake signals Part I	NHESS 7: 535-541	Full text verified
Freund, F.T. (2007b)	Pre-earthquake signals Part II	NHESS 7: 543-548	Full text verified
Freund, F.T. (2010)	Toward a Unified Solid State Theory	Acta Geophysica 58: 719-766	Full text verified
Freund, F.T. (2019)	Co-seismic Earthquake Lights	Pure & Applied Geophysics 176: 3439-3450	Full text verified
Freund, Takeuchi & Lau (2006)	Electric currents from stressed igneous rocks	Phys. Chem. Earth 31: 389-396	Confirmed real
St-Laurent, Derr & Freund (2006)	Earthquake Lights and P-hole Carriers	Conference proceedings	Full text verified
Bleier et al. (2009)	ULF, air conductivity, IR — Alum Rock M5.4	NHESS 9: 585-603	Full text verified
Bleier et al. (2013)	Ground-based and space-based EM monitoring	TERRAPUB chapter	Full text verified
Grant et al. (2011)	Ground Water Chemistry & Animal Behavior	IJERPH 8: 1936-1956	Full text verified
Balk et al. (2009)	Oxidation of water to H ₂ O ₂ at rock-water interface	EPSL 283: 87-92	Confirmed real
Baron et al. (2022)	EMR at seismogenic fault — Obir Cave	Engineering Geology 311: 106912	Full text verified
Teodorani, M. (2004)	Long-Term Scientific Survey of Hessdalen	J. Scientific Exploration 18(2): 217-251	Full text verified
Teodorani, M. (2024)	Investigating UAP Using Astronomical Techniques	Limina 1(1): 40-54	Full text verified
Vargemezis et al. (2024)	VLf survey — Hessdalen lights	J. Applied Geophysics 226: 105398	Full text verified
Whitehead & Ulusoy (2025)	EQL: Rayleigh Scattering, Kaikoura	Atmosphere 16(3): 277	Full text verified — open access
Igarashi et al. (1995)	Ground Water Radon — Kobe earthquake	Science 269: 60-64	Full text verified
Nikitin & Ivankina (1995)	Mechanisms of Piezoelectric Active Rocks	Textures & Microstructures 25: 33-43	Full text verified
Bishop, J.R. (1981)	Piezoelectric effects in quartz-rich rocks	Tectonophysics 77: 297-321	Confirmed real
Nitsan, U. (1977)	EM emission from quartz-bearing rock fracture	Geophys. Res. Lett. 4: 333-336	Confirmed real
Hanson & Rowell (1982)	EM Radiation from Rock Failure	USBM RI 8594	Full text verified
Paiva & Taft (2010)	Dusty plasma mechanism — Hessdalen lights	JASTP 72: 1200-1203	Confirmed real
Tsyтович et al. (2007)	Plasma crystals to inorganic living matter	New J. Physics 9: 263	Confirmed real

Citation	Title	Journal / Source	Status
Turner, D.J. (2003)	The missing science of ball lightning	J. Scientific Exploration 17(3): 435-496	Confirmed real
Monari et al. (2013)	Hessdalen — A Perfect Natural Battery	ICPH Articles	Confirmed real
Strand, E.P. (1984)	Project Hessdalen Final Technical Report	Project Hessdalen	Full text verified
Hauge, B.G. (2010)	Transient luminous phenomena — Hessdalen	Acta Astronautica	Confirmed real
Derr, J.S. (1973)	Earthquake lights: review of observations	BSSA 63: 2177-2187	Confirmed real
Derr, J.S. (1986)	Luminous phenomena and rock fracture	Nature 321: 470-471	Confirmed real
St-Laurent, F. (2000)	Saguenay earthquake lights 1988-1989	Seismolog. Res. Lett. 71: 160-174	Confirmed real
Strumik et al. (2021)	Lightning-ionosphere ULF link via Swarm	GRL 48, e2020GL091507	Full text verified — open access
Bürgesser, Nicora & Ávila (2012)	Catatumbo Lightning characterization	JASTP doi:10.1016/j.jastp.2012.01.013	Full text verified
Warren, J.P. / L.E.M.U.R. (2004)	Report on the Cause of the Brown Mountain Lights	L.E.M.U.R., Asheville NC	Full text verified — primary field validation dataset
Straser, V. (2016)	Ball lightning and tectonic stress — Taro Valley	Italian geophysics literature	Confirmed real
Byerlee, J.D. (1993)	Model for episodic flow of high-pressure water in fault zones	Geology 21: 303-306	Primary Pathway 6 citation
Iannaccone et al. (2018)	Gran Sasso groundwater EC anomaly — 2016 Amatrice M6.0	Scientific Reports	60-day groundwater EC precursor — Pathway 6 validation
Thompson & Gist (1993)	Seismoelectric wave detection at gas-water interface	Leading Edge, 12: 1887	Primary seismoelectric effect citation
Liu et al. (2024)	Seismoelectric imaging of aquifer interface	Geophysical Research Letters	Full text verified — electrokinetic imaging
Cooper et al. (1965)	Response of well-aquifer systems to seismic waves	J. Geophys. Res. 70: 3915	Foundational seismic/aquifer coupling paper

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Active research collaborations: Fred Pallesen (CEO, Project Hessdalen); Jean Vézina (Quebec earth lights researcher); Alex Yun (China, dusty plasma electromagnetic soliton model); Henning Kuersten (independent researcher, Brown Mountain and APP field investigation). The GPDM v2.5 has been shared with these collaborators.

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