Title: The Geological Pathway Diversity Model (GPDM): A Unified Classification and Predictive Framework for Anomalous Luminous Phenomena

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GEOLOGICAL PATHWAY DIVERSITY MODEL

A Multi-Site Framework for Atmospheric Plasma Phenomena

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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. Five 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; and (5) radon/alpha-ionization dusty plasma formation. A four-variable state equation governs output intensity and type across all pathways. Three primary field sites — Brown Mountain (North Carolina, USA), 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 three-sensor monitoring package (ULF magnetometer, air ion counter, IR thermal camera) at geologically qualified sites is proposed as the primary validation pathway.

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 H_2O-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 H_2 gas while the oxygens are oxidized from O^{2-} to O^-, creating peroxy links of the form $O_3Si\text{-}OO\text{-}SiO_3$. 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 $O^-\text{-}O^-$ bond, releasing a mobile positive hole ($h^\bullet$) via a two-step process in which a neighboring O^{2-} donates an electron to the broken bond, becoming O^- and thus itself a mobile charge carrier. 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 (O2- donating an electron to adjacent O-, advancing the hole by one atomic spacing of ~2.8Å at phonon frequencies of ~10^12 Hz). This propagation speed has been confirmed in laboratory impact experiments and in 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, calculated by King & Freund (1984) using Schottky barrier theory, 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 (~2×10^6 V/cm at corners), producing field ionization of O2 molecules (positive airborne ion emission) followed by corona discharge onset when the field drives ionization avalanches. 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 as electron showers from the discharge neutralize the positive surface charge — 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 in a confined asperity volume 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 Five-Pathway Classification System

The GPDM classifies atmospheric plasma phenomena at recurrent sites into five geological activation pathways. Each pathway reflects a distinct primary mechanism of charge carrier generation or plasma formation, though pathways frequently co-occur at the same site with local geology and tectonic conditions determining which is dominant. The OR logic structure is critical: the four-variable state equation (Section 4) operates as a parallel system — a single pathway achieving threshold activation is sufficient to produce observable output. Sites where multiple pathways are simultaneously active produce the most complex and sustained phenomenology.

Pathway 1 — P-hole / Peroxy (Freund Mechanism)	
Host Geology	Mafic igneous rocks (gabbro, basalt, granite, anorthosite). PHP density highest in rocks crystallized from H2O-laden magmas.
Trigger	Deviatoric stress — tectonic loading, S-wave shear. Dislocation movement intersects peroxy links, releasing mobile h• charge carriers.

Output	Pre-seismic ULF magnetic pulses; positive airborne ion emission; corona discharge at topographic highs; co-seismic EQL flash (plasma burst mode); satellite IR thermal anomaly; ionospheric TEC perturbation; groundwater H2O2 formation.
Key Sites	Saguenay, Quebec (1988 M6.5 documented EQL); Kobe, Japan (1995 M7.2); Alum Rock, CA (2007 M5.4 multi-instrument); Lima, Peru (2007 M8.0); Matsushiro, Japan (1965-67).
Primary Citations	Freund 2003, 2007a, 2010, 2019; St-Laurent, Derr & Freund 2006; Bleier et al. 2009, 2013; Grant et al. 2011.

Pathway 2 — Textural Piezoelectric	
Host Geology	Quartz-bearing rock with oriented electric axis polarity. Requires lattice preferred orientation PLUS polar axis alignment — specifically: hydrothermal vein quartz in fault zones; high-grade metamorphic quartzite with Leydolt/Dauphine twinning.
Trigger	Stress application along polar axis direction; shear stress on Dauphine-twinned quartzite. Condition: both crystallographic texture AND polarity orientation required for net macroscopic field.
Output	Net electric field emergence at rock surface; plasma initiation; EQL in quartz-rich geological settings; broadband EM emission during fracture (8-40 kHz dominant).
Key Sites	Kaikoura, NZ (greywacke, 2016 M7.8 documented EQL); Hessdalen, Norway (vein quartz component); Brown Mountain, NC (Appalachian metamorphic quartzite, predicted).
Primary Citations	Nikitin & Ivankina 1995; Bishop 1981; Whitehead & Ulusoy 2025; Nitsan 1977; Hanson & Rowell 1982.

Pathway 3 — Triboelectric / Microcracking	
Host Geology	Any brittle quartz-bearing rock undergoing fracture. Enhanced in texturally aligned metamorphic quartzite and granite with high stress drop events.
Trigger	Brittle fracture events with discrete stress drops; microcracking; grain boundary friction. EM emission scales with stress drop magnitude (crack size), not stress level.
Output	Broadband EMR impulses concentrated below 40 kHz; directional radiation pattern; correlated with acoustic emission. Does not produce sustained plasma phenomena alone.
Key Sites	Obir Cave fault, Eastern Alps (documented ULF/LF EMR monitoring); Galena Mine quartzite, Idaho (laboratory documented); Edgar Mine, Colorado (seismic tomography validated).
Primary Citations	Baron et al. 2022; Hanson & Rowell 1982; Nitsan 1977; Rabinovitch et al. 1995, 2000, 2001.

Pathway 4 — Electrochemical / Atmospheric (Natural Battery)	
Host Geology	Sites with electrochemically differentiated mineral deposits producing galvanic potential across fault geometry. Specifically: sulfide mineral oxidation/reduction couples separated by fault or valley geometry with groundwater ionic transport.
Trigger	Continuous electrochemical current driven by mineral oxidation/reduction differential. Circuit closure through electrolytic groundwater conductivity. Does NOT require seismic stress input — operates under sustained tectonic loading below fracture threshold.

Output	Long-duration (seconds to hours) thermally self-regulating plasma orbs; clustering effect; thermally stable across luminosity changes; IR + radar signatures; VLF Doppler-like signals. Primary mechanism for sustained earth lights distinct from co-seismic EQL.
Key Sites	Hessdalen, Norway (primary documented case — iron/zinc/copper mineral battery confirmed by VLF survey); Marfa, Texas (spectroscopic documentation).
Primary Citations	Teodorani 2004; Turner 2003; Monari et al. 2013; Vargemezis et al. 2024; Zou 1995.

Pathway 5 — Radon / Alpha-Ionization (Dusty Plasma)

Host Geology	Uranium/thorium-bearing rock in fault zones with radon emanation pathways. Sulfide minerals with associated radioactive trace elements. Radon concentration in groundwater proportional to U concentration in adjacent aquifer rocks.
Trigger	Radon-222 decay (half-life 3.8 days) produces alpha particles → air/dust ionization (~10^5 ion pairs/cm^3). Microcrack formation reduces effective grain size, releasing radon to groundwater. P-hole activity (Pathway 1) may chemically mobilize radon, coupling Pathways 1 and 5.
Output	Coulomb crystal cluster formations in dusty plasma; long-duration luminous plasmoids with helium spectral signature (alpha decay product); background ionization floor (30-300 ions/cm^3/sec) that Pathway 1 corona discharges amplify to 10^5+ ions/cm^3.
Key Sites	Hessdalen, Norway (helium spectral signature detected; Paiva & Taft 2010 Coulomb crystal model); Kobe precursor zone (10x radon spike 9 days before M7.2).
Primary Citations	Paiva & Taft 2010; Igarashi et al. 1995; Tsytovich et al. 2007; Freund 2010 (p-hole/radon coupling).

Pathway 6 — Seismoelectric / Hydroelectric Coupling (NEW — v2.3)

Host Geology	Water-saturated fractured fault zone geology with ionic groundwater in porous rock capillaries. Applies at any GPDM candidate site with a documented aquifer, surface water (lake, river, spring), or freshwater-saltwater interface. Most potent where Pathway 4 (natural battery) and groundwater co-exist — sulfide mineral deposits + conductive aquifer create a superposition of electrochemical and electrokinetic mechanisms. Archie's Law governs the conductivity of water-bearing rock: porosity and ionic concentration of groundwater determine the charge carrier mobility of the saturated zone.
Trigger	Acoustic stress waves (seismic P-waves, microseismic events, tidal compression) propagate through water-saturated porous rock. Relative motion of ionic groundwater through rock capillaries under acoustic pressure generates streaming potentials — electric dipoles that radiate detectable EM fields at surface (seismoelectric effect). In non-homogeneous formations, the acoustic wave generates oscillating fluid flow and a corresponding oscillating EM field. Secondary trigger: rapid atmospheric electric field changes from CME magnetospheric compression couple through the conductive water table, modulating electrokinetic streaming potential and amplifying Pathway 4 discharge. Groundwater electrical conductivity (EC) anomalies precede seismic events by up to 60 days — episodic high-pressure water flow between fault zone compartments generates precursory electrical and magnetic signals (Byerlee 1993). Gran Sasso borehole monitoring detected significant EC anomalies 60 days before the 2016 Amatrice M6.0 earthquake.
Output	Oscillating EM field emission at surface coincident with acoustic stress wave arrival; groundwater EC anomaly detectable in borehole or surface water monitoring (days to 60 days pre-event); streaming potential voltage measurable between ground stakes; long-duration sustained APP when electrokinetic streaming superimposes on Pathway 4 natural battery discharge — water acts as both the electrolyte AND the acoustic-to-electromagnetic transducer simultaneously.

Key Sites	Hessdalen, Norway (multiple lakes; sulfide aquifer; Pathway 4 + 6 superposition — primary candidate); Brown Mountain, NC (fault zone groundwater; L.E.M.U.R. telluric current data consistent with electrokinetic streaming); Taro Valley, Italy (carbonate aquifer in Apennine thrust belt; 750+ APP reports; natural gas + water + fault geology = Variable 3 + Pathway 6 superposition); Uinta Basin, Utah (hydrocarbon-bearing groundwater; freshwater-brine interface in sedimentary basin); Canadian Shield candidate sites (precambrian basement with deep aquifer systems); All coastal GPDM sites where freshwater-saltwater interface exists.
Primary Citations	Byerlee (1993) — groundwater EM precursor; Seismoelectric method (Thompson & Gist 1993; Haartsen & Pride 1997); Iannaccone et al. (2018) — Gran Sasso groundwater EC anomaly 60 days pre-Amatrice; Cooper et al. (1965) — seismic wave/aquifer coupling; USGS groundwater earthquake effects database; Liu et al. (2024) — seismoelectric aquifer imaging (GRL).

> **Note on Pathway 1 / Pathway 4 Bifurcation:** Both Pathway 1 (co-seismic EQL) and Pathway 4 (sustained plasma orbs) may share p-hole surface arrival as a common trigger. The bifurcation point is Variable 3 (atmospheric state): dry conditions with high topographic relief favor corona discharge and EQL flash; humid valley conditions with electrochemical confinement mechanism favor thermally self-regulating plasma orb formation. Brown Mountain (dry Appalachian ridges) is predicted to be a predominantly Pathway 1/2 output site; Hessdalen (humid Norwegian valley with natural battery geometry) is a predominantly Pathway 4 output site. The same fundamental charge carrier physics underlies both.

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 is not a simple linear function — it 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 (dσ/dt)

Controls the rate of dislocation generation and therefore the rate of PHP dissociation and h• production. Stress input sources are multiple: 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 10cm 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. This means tidal cycles modulate the output intensity of an already-active system rather than switching it on and off discretely. Variable 1 can be near-zero at Hessdalen (seismicity below M2.5 since 2000) while Pathway 4 continues operating — confirming that Variable 1 is not required for all pathways.

Variable 2 — Carrier Density / Lithology (ρ_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. Also present in all igneous and metamorphic crustal rock per Freund's universality statement — the question is magnitude rather than presence. For Pathway 2, Variable 2 encompasses both quartz content and the presence of oriented electric axis polarity (the Nikitin & Ivankina (1995) condition): lattice preferred orientation alone is insufficient — polarity orientation is required for net macroscopic piezoelectric field emergence.

Variable 3 — Atmospheric / Environmental State (Ψ_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 via Turner's thermochemical refrigeration mechanism, producing sustained plasma orbs (Pathway 4 output). Low humidity or high topographic relief with discrete convex geometry favors corona discharge and EQL flash (Pathway 1/2 output). Also governs the efficiency of Pathway 5 (radon/dusty plasma): water vapor density affects Coulomb crystal formation in alpha-ionized dusty plasma. The winter dominance and humidity correlation of Hessdalen events (Strand 1984, Teodorani 2004) is a direct expression of Variable 3.

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 (governing h• flow direction); topographic geometry at emergence point (governing electric field concentration); and circuit closure mechanism — three natural pathways identified by Freund (2010): (i) downward electron flow to the n-type conducting lower crust at ~500°C; (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

Three primary field sites anchor the GPDM's comparative multi-site framework. Each site has independent documentation of recurrent atmospheric plasma phenomena, geological characterization that assigns it to one or more GPDM pathways, and an active research relationship supporting future monitoring deployment.

Site	Geology	Phenomena	Active Pathways	Status
Brown Mountain, NC, USA	Appalachian fold-thrust belt; metamorphic quartzite with deformation texture	Recurrent luminous orbs documented since 19th century. Events concentrated at	1 (primary), 2 (active — textured quartzite), 3 (microcracking), 5 (radon — Geiger anomalies	Primary GPDM field site. L.E.M.U.R. 2004 report (Warren, J.P.) formally cited as

	(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). Quartz and magnetite layers documented by L.E.M.U.R. field investigation.	ridges and topographic highs — consistent with p-hole corona discharge geometry (Freund 2003). L.E.M.U.R. (2004) independently documented: Geiger ionization anomalies (Pathway 5); erratic telluric ground currents milliVolts to >1V (Pathway 1); VLF anomalies at ~140 kHz (Pathway 3); Kp >= 5 correlation (Variable 1); rain correlation (Variable 3); thrust fault encirclement (Variable 4). All 10 major L.E.M.U.R. findings map directly onto GPDM pathway predictions.	documented)	independent field validation dataset. Active research collaboration with Warren / L.E.M.U.R. team pending (via Mobius/Vanderburgh). Outreach to Appalachian State University researcher sent.
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 by Vargemezis et al. 2024 VLF survey); 1 (substrate present, seismicity below M2.5 since 2000); 2 (vein quartz component); 5 (radon/dusty plasma — helium spectral signature)	Active collaboration. GPDM v2.3 sent to Fred Pallesen (CEO, Project Hessdalen). Introductions made to Daniel Nordvik and Henning Kuersten via Fred.

		confirmation).		
La Pena de Juaica, 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.
Mt. Kholat Syakhl / Northern Urals, Russia	Main Ural tectonic fault line; Precambrian metamorphic basement with quartz-bearing rock; mixed iron, copper, and sulfide mineral deposits. Documented compass anomalies up to 30 degrees consistent with anomalous telluric current flow. Mt. Chistop radar site failure (semiconductors burned, copper wire turned to ash, ball lightning from telephones) — consistent with Variable 4 discharge point siting.	Multiple independent APP sightings February-March 1959 by military search personnel, meteorology service, and civilian hiking groups. Slow-moving plasma orbs, clustering, rectangular light forms. The 1959 Dyatlov Pass deaths represent the most dramatic documented fatality event associated with APP plasma burst mode discharge in modern history. Beta radiation on victim clothing (Pathway 5). Blast wave injuries consistent with near-field plasma burst mode (Teodorani diffusion/explosion model).	1 (primary — p-hole in metamorphic basement, plasma burst mode); 2 (textured quartzite); 5 (radon — beta radiation confirmed on victim clothing)	New GPDM candidate site (v2.1). Kuersten (2021) APP hypothesis formally connected to GPDM geological activation layer. Active collaboration with Henning Kuersten and Project Hessdalen network.
Taro Valley (Val di Taro), Emilia-Romagna, Italy	Northern Apennines fold-thrust belt; TAL (Taro) and LEF (Livorno-Empoli) boundary fault systems; Plio-Quaternary sedimentary basin overlying Tortonian-	750+ ball lightning and APP reports documented since 1900 in Emilia-Romagna province. Events concentrated along fault systems and near oil/gas infrastructure.	1 (primary — p-hole in Apennine thrust fault geology); 3 (triboelectric microcracking); Variable 3 modifier — natural gas in atmosphere provides	New GPDM candidate site (v2.2). Added based on Kuersten (2021) field documentation and Straser tectonic APP correlation study. High natural gas

	Messinian continental-marine deposits; high natural gas field density (48% of Italy's gas extraction from this province). Multiple historical earthquakes Mw 5-6.5 documented along Apennines Deformation Front (ADF) and Apennines Range Front (ARF).	Italian researcher Valentino Straser documented direct field observation of APP emerging from clayey soil in a ravine along the Taro Valley Seismic Line. Noted correlation between tectonic stress (piezoelectricity), natural gas ionization, and plasma formation.	additional ionization substrate	density creates unique Variable 3 atmospheric chemistry conditions — potential mycelial/hydrocarbon soil outgassing modifier.
Southern California Fault Zones, USA	San Andreas Fault system (right-lateral strike-slip, ~1300 km); Garlock Fault (left-lateral, east-west); Elsinore Fault; San Jacinto Fault; Newport-Inglewood-Rose Canyon Fault. Predominant lithology: granitic and metamorphic basement (Peninsular Ranges Batholith) with extensive mafic intrusions. High PHP density substrate.	NUFORC database (2000-2023, 112,914 sightings) shows elevated sighting density along Pacific Coast and Mountain West fault corridors that is inconsistent with population density distribution alone. The Garlock, San Andreas, and Elsinore fault systems all show elevated density in per-capita sighting maps. Correlation pattern matches GPDM GIS spatial prediction methodology — sighting clusters trace fault geometry rather than urban centres.	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)	New GPDM candidate zone (v2.2). Added based on NUFORC heatmap correlation with USGS fault mapping provided by Kuersten. Statistical correlation analysis of sighting density vs fault proximity pending.
Uinta Basin / Skinwalker Ranch, Utah, USA	Uinta Basin — Eocene sedimentary basin overlying Precambrian basement. Uinta Mountains to	Decades of documented anomalous phenomena at Skinwalker Ranch including luminous orbs of	1 (p-hole — Precambrian quartzite basement); 4 (electrochemical — sedimentary basin/basement	New GPDM candidate site (v2.2). Added based on NUFORC heatmap data and Kuersten flagging.

	north composed of Precambrian quartzite (high PHP potential). Significant oil and gas production with associated hydrocarbon geology. Documented geomagnetic anomalies in the region.	varying colors, reported electrical effects, and unexplained aerial phenomena. Utah hotspot clearly visible in NUFORC per-capita sighting maps. Uinta Basin geology provides sedimentary-basement interface conditions consistent with Variable 4 circuit closure.	interface with hydrocarbon geology); Variable 3 — hydrocarbon/gas atmospheric modifier	Active collaboration pathway via Joshua P. Warren (L.E.M.U.R.) who has existing Skinwalker Ranch industry relationships. Tanja contact at Project Hessdalen also has Ranch connections.

> **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.

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 10cm vertical at the Obir Cave fault monitoring site using the Goddard GOT00.2 ocean tide model, 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 (three distinct lifetime populations documented in gabbro at 48 MPa). 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.

For Brown Mountain (Appalachian location), tidal prediction must account for both solid earth tides and the microseismic background from Atlantic Ocean wave activity (Bromirski 2001 established transcontinental propagation of microseismic energy from coastal wave-wave interactions). The dominant microseismic source areas — near southern Massachusetts coast and south of Cape Hatteras — are within Rayleigh wave propagation range of the Appalachians. This provides a continuous low-amplitude stress input to Brown Mountain's geological system that is modulated by ocean storm state independent of tidal cycles.

Specific tidal predictions for Brown Mountain and Hessdalen require site-specific tidal loading models. This is identified as a primary next development step for GPDM v3.

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.

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).

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. These predictions will be formally documented in a companion technical note and submitted for independent geological assessment 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.

The 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 three-sensor 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.

The null-site test is explicitly designed to be run in parallel with the monitoring network deployment proposed in Section 9. It converts the deployment from a descriptive monitoring exercise into a controlled scientific test.

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.

A meteor's color tells you what it is made of. Sodium burns yellow-orange. Magnesium burns white-blue. Iron burns orange-red. Calcium burns violet. The spectral emission is a direct function of the elemental composition of the material being excited. The same physics applies to APP color output: the corona discharge or plasma event ionizes whatever molecules are present at the discharge zone — rock minerals, soil chemistry compounds, atmospheric gases, groundwater volatiles. The color observed is the spectral emission of those specific elements being excited.

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. Decades of documented 'unreliable eyewitness reports' become an inadvertent geological survey dataset when filtered through this lens.

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). Consistent with documented red-orange coloration in multiple Appalachian region APP reports.

Blue to blue-green: Ionized nitrogen dominant (atmospheric) or copper compounds (geological). Blue-violet at high altitude or low-mineral events where atmospheric nitrogen dominates. 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. Documented at Dyatlov Pass incident and M-Zone Russia — both high-energy events on the same Ural fault line with metamorphic basement geology.

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. Sulfide-rich sites more yellow-green. This is testable against existing datasets — Project Hessdalen AMS color data, the M-Zone photographic record, the Dyatlov case file photographs, and the L.E.M.U.R. Brown Mountain video archive.

The monitoring network's calibrated color camera deployment (Section 10) is not merely documenting that APP events occur. It is performing real-time mineral spectroscopy of the discharge zone. Paired with the geological substrate characterization, it provides a continuous, automated spectral verification of the GPDM's pathway assignments at each site.

11. Pathway 6 — Seismoelectric and Hydroelectric Coupling (v2.3)

Pathways 1-5 address the geological generation of charge carriers and plasma in crustal rock. A critical amplifying mechanism was absent from the original framework: the role of ionic groundwater as both an electrical conductor and an acoustic-to-electromagnetic transducer. Pathway 6 formally addresses this gap.

11.1 The Seismoelectric Effect

When an acoustic stress wave — seismic P-wave, microseismic event, tidal compression, or infrasound — 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 does not create new charge carriers — it 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 that converts mechanical stress into electromagnetic output.

11.2 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, consistent with 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 in the fault zone, allowing groundwater to migrate between compartments of different ionic concentration. The mixing of groundwaters with different mineral content changes the electrical conductivity of the water in monitored wells and surface water bodies. This conductivity change is both the precursor signal and the Pathway 6 activation indicator — the same fault zone water migration that changes EC also provides the ionic current carrier for seismoelectric EM emission.

11.3 The CME-Water-Pathway 6 Chain

The most significant new connection identified in v2.3 is the complete chain linking solar activity to ground-level APP discharge through the water table. A coronal mass ejection arriving at Earth compresses the magnetosphere, producing rapid changes in the global atmospheric electric circuit.

These changes manifest as sudden Schumann resonance anomalies and EFM spikes at ground level — already captured by the GPDM monitoring package as Variable 1 modulation.

The new mechanism: rapid atmospheric electric field changes from CME magnetospheric compression couple into the ground through the conductive water table. Groundwater EC responds to the changing electric field. In water-saturated fault zone geology, this response modulates the electrokinetic streaming potential — effectively using the CME as a remote trigger for Pathway 6 discharge. The complete chain: CME at the Sun → 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.

KEY FINDING: This chain is the first proposed mechanism connecting solar weather events directly to ground-level geological plasma discharge through a physically documented intermediate — the water table. Every link is independently documented in the peer-reviewed literature. The Presignal Field Node monitoring package captures every link in this chain simultaneously.

11.4 Pathway 6 Sites

Pathway 6 is most active at sites where ionic groundwater is in continuous contact with fault zone geology. All current GPDM primary sites have a Pathway 6 component: Hessdalen (sulfide aquifer, multiple lakes — Pathway 4 + 6 superposition, the strongest theoretical combination); Brown Mountain (Appalachian fault zone groundwater — L.E.M.U.R. telluric current data consistent with electrokinetic streaming); Taro Valley (carbonate aquifer in Apennine thrust belt — natural gas + water + fault = Variable 3 + Pathway 6 superposition); Uinta Basin (hydrocarbon-bearing groundwater, freshwater-brine interface); all coastal GPDM candidate sites with freshwater-saltwater interfaces.

The subtraction methodology implication: any APP sighting near surface water — lake, river, spring, coastline — should now be evaluated for Pathway 6 activity before classification. The proximity to water is not incidental. It is a geological indicator that Pathway 6 may be the primary or amplifying mechanism.

11.5 Monitoring Addition — Water EC Probe

A TDS/EC water conductivity probe ($12, operating -10°C to +60°C, heater-mitigated for cold sites) 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 — either increase or decrease from baseline — 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). This is the longest-range temporal precursor in the entire monitoring package.

12. Catatumbo — Contrast Case and Variable 3 Clarification

The Catatumbo Lightning phenomenon (Relámpago del Catatumbo) 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 World

Wide Lightning Location Network (WWLLN) and Lightning Imaging Sensor (LIS) data — requires a significant reassessment.

Bürgesser et al. (2012) confirm that Catatumbo's semiannual activity pattern (two maxima: May and October; minimum January-February) 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 (Falcón & Quintero 2010) is explicitly falsified: it predicts maximum activity during the dry season (December-May), 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 removed from the dry thunderstorm Variable 3 modifier anchor position.

> **Revised GPDM classification:** Catatumbo 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. The dry thunderstorm Variable 3 modifier anchor is reassigned to the American Southwest (Time Warp, Nevada) and Atacama margins where geological discharge operates in arid atmospheric conditions without dominant meteorological convection systems.

11. Proposed Monitoring Network

The validation pathway for the GPDM is a standardized multi-instrument monitoring network deployed at geologically qualified sites. 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 (v2.2): (1) ULF induction magnetometer (0.01-12 Hz, sensitivity ~0.1 pT/√Hz 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 μm) for non-thermal IR emission and night-time cooling slope analysis; (4) Calibrated color camera for APP spectral color documentation — mineral composition diagnostic (see Section 9); (5) Electric Field Meter (EFM) for direct surface electric field measurement — detects p-hole surface charge accumulation before corona discharge threshold, providing earliest possible pre-event signal.

Optional Enhancement: (6) Geiger counter (sensitivity to microRem, detecting alpha, beta, gamma) 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.

> **Note on EFM and Geiger additions (v2.2):** Both instruments were recommended by Henning Kuersten (independent researcher, author of The Dyatlov Pass Mystery — NOT A Cold Case, 2021) based on his field experience at Brown Mountain and analysis of the Dyatlov Pass incident. The EFM is arguably the single most important pre-discharge instrument — it measures the surface electric field directly, providing a real-time readout of h• charge accumulation at the monitoring site. The Geiger counter's role in detecting APP-associated ionization events was independently documented by the L.E.M.U.R. field team at

> Brown Mountain (Warren 2004) and is consistent with Pathway 5 radon/alpha ionization mechanisms. Both are now standard in the GPDM monitoring package.

11.1 ULF Discrimination Layer — Strumik et al. (2021)

A critical noise discrimination challenge is distinguishing geological p-hole ULF from lightning-generated ULF. Strumik et al. (2021) provide the first experimental confirmation that lightning generates ULF fluctuations detectable in the upper ionosphere via Swarm satellites, 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.

11.2 Anthropogenic Circuit Closure — Variable 4 Secondary Modifier

A secondary Variable 4 modifier is proposed for investigation: several of the most vivid documented APP encounters occur in proximity to power infrastructure. Yakimov (2002) was standing next to a transformer when his encounter began. Rudkovskiy's encounter ended with a loud electrical discharge snap. The Colares, Brazil accounts repeatedly involve encounters near water and electrical conductors. The hypothesis: power lines and transformers may act as secondary circuit closure mechanisms for geological p-hole ground currents, lowering the discharge threshold at specific locations without being independent energy sources. This is testable by mapping APP encounter density against infrastructure proximity controlling for geological substrate.

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.

12. 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.

Version 2.3 additions: Pathway 6 (Seismoelectric/Hydroelectric Coupling) formally added — electrokinetic streaming potential in water-saturated fault zone geology; groundwater electrical conductivity anomaly as 60-day pre-seismic precursor; CME-water table-Pathway 6 coupling chain documented; water conductivity probe added to monitoring package; subtraction methodology updated to include Pathway 6 elimination criteria. Version 2.2: Taro Valley Italy, Southern California fault zones, and Uinta Basin/Skinwalker Ranch added as new candidate sites; EFM and Geiger counter added to standard monitoring package. Version 2.1: APP color as geological mineral indicator; Catatumbo contrast case; Strumik et al. (2021) ULF discrimination; L.E.M.U.R. Brown Mountain validation; Dyatlov Pass and M-Zone candidate sites.

The framework generates testable predictions at three levels: site-specific (tidal calendar predictions for Brown Mountain and Hessdalen); inter-site (geological matching predictions for new candidate sites including Dyatlov Pass region and M-Zone); and null-site (falsification predictions for geologically non-qualifying sites).

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.

13. 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.

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 H2O2 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
Tsytovich et al. (2007)	Plasma crystals to inorganic living matter	New J. Physics 9: 263	Confirmed real
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
Kuersten, H. (2021)	The Dyatlov Pass Mystery — NOT A Cold Case	1STEIN Publishing (4th ed.)	Full text verified — direct communication with author
Warren, J.P. / L.E.M.U.R.	Report on the Cause of the	L.E.M.U.R., Asheville NC	Full text verified —

(2004)	Brown Mountain Lights		primary field validation dataset
Straser, V. (2016)	Ball lightning and tectonic stress — Taro Valley	Italian geophysics literature	Confirmed real — Taro Valley APP/fault correlation
NUFORC Database (2000-2023)	112,914 UFO sighting reports	National UFO Reporting Center	Public dataset — pending fault correlation analysis
Byerlee, J.D. (1993)	Model for episodic flow of high-pressure water in fault zones before earthquakes	Geology 21: 303-306	Primary Pathway 6 citation — groundwater EM precursor mechanism
Iannaccone et al. (2018)	Gran Sasso groundwater EC anomaly before 2016 Amatrice M6.0 earthquake	Scientific Reports	60-day groundwater EC pre-seismic anomaly — Pathway 6 validation
Thompson & Gist (1993)	Seismoelectric wave detection at gas-water interface	Leading Edge, 12: 1887	Primary seismoelectric effect citation — acoustic to EM conversion in water-saturated rock
Liu et al. (2024)	Seismoelectric imaging of aquifer interface	Geophysical Research Letters	Full text verified — electrokinetic imaging methodology
Cooper et al. (1965)	Response of well-aquifer systems to seismic waves	J. Geophys. Res. 70: 3915	Foundational seismic/aquifer coupling paper — USGS cited