SOLAR-DRIVEN GEOMAGNETIC ENERGY:

MODELING DEEP GEOMAGNETICALLY INDUCED CURRENTS AND GEOTHERMAL DYNAMICS IN YELLOWSTONE NATIONAL PARK

by

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DEDICATION

Thank you to my three daughters and husband, who have supported my goals throughout the years.

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TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

ABSTRACT

Solar events impact Earth's magnetosphere, generating magnetic variations that drive energy transfer into Earth's conductive materials. This process induces geomagnetically induced currents (GICs), which, through thermodynamic principles, facilitate Joule heating through thermal convection. These energy transfers are proposed to correlate with changes in their surrounding ecosystems. Previous studies have linked geomagnetic storms to seismic activity, hurricane cycles, geothermal fluctuations, and deep interior thermal dynamics, suggesting that these energy shifts drive ecosystem variations. Tracking the flow of magnetic thermodynamics provides an understanding of interior energy drivers in surface temperature changes, soil composition, and species-specific resilience.

Yellowstone National Park is proposed for modeling geological thermodynamics due to its highly conductive underground plume of partly molten rock feeding into the caldera. Known rhyolite area deposits with high electrical conductivity create a natural conduit for GIC-driven Joule heating under geothermal features. Tracking variations in the geochemistry of rhyolite mineral dissolution in geothermal waters, deep thermal dynamics linked to magnetic activity can be traced. This proposed study connects solar-induced geomagnetic variations and internal geological processes, providing a potential mechanism for understanding the causality behind their ecosystem changes.

CHAPTER ONE

SOLAR EVENT FLOW OF GEOLOGICAL THERMODYNAMICS

Introduction

The Sun is our primary energy source, providing electromagnetic radiation (EMR) that drives atmospheric, oceanic, and biological activity. Although our current understanding suggests that solar events (Solar Flares, Coronal Mass Ejections (CME), and continuous solar wind) interacting with the magnetosphere dissipate in isolation, the principles of thermodynamics dictate that energy can transfer or transform, transferring into geomagnetic storms. Electromagnetic radiation (EMR), ejected by solar events, interacts with the magnetosphere (Kono & Roberts, 2002)generating geomagnetic storms (Gvishiani & Soloviev, 2020a) that can cycle up to several days. These geomagnetic storms can possibly induce even slight seismic activity (Chen et al., 2020a), creating shifts in soil composition, increasing species-specific forest resilience (Gao, 2024), and contributing to large-scale ecosystem shifts to the minor internal mechanosensitive channels in plant root biological responses (Tyagi et al., 2023). The significance is seen in subtle small shifts creating significant adaptation responses. There is also a correlation between significant years of seismic activity and significant geothermal activity(Ball et al., 2002) , further presenting a more substantial case of causality, traceable through various ecological systems, specifically geothermal features, which will be discussed in later sections.

To reiterate, solar events eject electromagnetic radiation toward our atmosphere, connecting with our magnetosphere and creating geomagnetic storms. Geomagnetic storms are variations in the magnetic field taken from ground electrical fields, creating geomagnetically induced currents (GICs) (Juusola et al., 2020). Ionosphere joule heating created by GICs when interacting with the high-altitude magnetosphere (Robinson & Zanetti, 2021) is the same concept presented in my proposed study, but to use this mechanism for interior induced electrical currents creating thermal energy driving internal processes. Current ground magnetometers capture surface GICs but are limited at any significant depth (Grayver, 2024). Our understanding of the geomagnetic field is created by the outer core's "geodynamo" process, with the force line leaving the magnetic north pole and reentering near the south pole (Lowes, 2007). Capturing surface variations is only allowing us to observe a portion of our magnetic field variations that influence the surface. However, using an observable natural feature that carries thermal energy from internal field variations into trackable ecological shifts, we can create a more comprehensive view of our internal magnetic field.

I propose in this review that GICs are also produced within deep magma chambers creating thermal energy, giving a mechanism of positive correlation with magnetic shifts driving seismic and geothermal activity. My study framework to track this particular thermodynamic flow of magnetic energy is through thermal energy from induced electrical currents driving geothermal activity observable from surrounding rock dissolution rates.

In this paper, I explore a study framework to bring awareness to implications of magnetic energy throughout interior Earth. Rock dissolution rates in geothermal activity, I propose to use as a conservative application to identify magnetic energy path inducing thermal energy that facilitate natural phenomena. Geothermal activity and influences on their surrounding ecosystems are the main focus for proposing causality of interior magnetic energy. The presence of deep induced magnetic energy facilitating geothermal activity creates a link for causality in seismic activity and surface temperature variations. Tracking a path of magnetic energy gives researchers another causality in significant ecosystem shifts. For instance, looking at the causality of mountain pine beetle (Dentroctonus ponderosea) infestation in Yellowstone National Park (YNP) would benefit from a resource of magnetic energy precursors that include all magnitudes of seismic shifts, surface temperatures, and geomagnetic storms increasing during specific years and geographical locations. Low-magnitude seismic frequency is continuously occurring, specifically noticeable in YNP's magmatic and geothermal systems *(U.S. National Park Service*, 2023), and has been significantly correlated as a global temperature predictor (Chen et al., 2020a; Viterito, 2016). Mountain pine beetle infestation increased significantly in the mid-1980s through the 1990s. While it is impossible to quantify a beetle outbreak with seismic activity mathematically, the infestation causality is justified in higher winter minimum temperatures (Buotte et al., 2016); it can also be correlated with surface temperature variations and earthquake swarms seen explicitly in Yellowstone in 1985 (*USGS*, 2004). In summary, low and high magnitudes of seismic activity release heat that would give causality to rising average winter temperatures, creating conditions favorable for mountain pine beetle infestations. Linking this causality to deep GIC variations influenced by geomagnetic storms give cause to look at Earths magnetic field as a driver in natural phenomenon.

Now, even positively correlating each of these phenomena, there are anomalies that suggest a possibility of energy build-up (Gao, 2024). These anomalies could indicate Joule heating through thermal convection in deeper currents, presenting another avenue for where these GICs are located. Relying on seismic activity to trace Joule heating presents limitations because it is more spread out in the sense of heat shifting large tectonic plates. Proposing to use geothermal activity, precisely the deposition and dissolution rate of mineral-rich rock in Yellowstone geothermal features, as a more accessible and localized indicator of deep GICs. This approach concentrates on Joule heating effects in deeper magma currents, as these geothermal features directly interact with this heat source. My research proposal would bridge the gap in our understanding of geomagnetic storms influencing deeper GICs-induced Joule heating in Earth's interior, providing a precise way to track this process while bypassing technological limitations.

In the following sections, I review thermodynamic principles and their relationship to Joule heating during atmospheric solar event interactions, establishing an understanding of the possible function of deeper Earth processes beyond current technological reach. I also review the geodynamo process to view the geomagnetic field and identify potential markers of deeper electrical currents. Markers provide a valuable path in geomagnetic storms as they correlate with natural phenomena such as hurricanes, oceanic temperature variations, seismic events, geothermal activity, and volcanic eruptions, presenting this flow of causality seen in patterns and recurring data anomalies, suggesting the possibility of deeper geomagnetically induced currents (GICs). Focusing on geothermal activity in my proposed study introduces the possibility of tracking magnetic energy flows, emphasizing the suitability of geothermal features for this purpose. YNP is an accessible site for geothermal activity that provides insight into interior currents and their broader implications. Following how the flow of magmatic energy continues into surrounding ecosystems and utilizing the flow on a planetary-scale process influenced by deep interior GICs illustrates the importance of tracking these interactions. Finally, my paper proposes a theoretical framework to predict variations associated with these phenomena and surrounding ecosystem showing implementations of my framework

CHAPTER TWO

CONCEPT FRAMING

Thermodynamics

The first law of thermodynamics follows energy conservation laws and states that energy is transferred and/or transformed from one form to another. Significant solar events, such as solar flares and coronal mass ejections (CMEs), release vast amounts of electromagnetic energy into the solar system, with the majority of that energy transformed into a geomagnetic storm with a portion of heat released from Joule heating through geomagnetic-induced currents (GICs). In the case of significant solar events, the energy from these events is extensive enough to penetrate through the magnetosphere and induce changes in the Earth's lithosphere and biosphere (Milan et al., 2017; Sadhukhan et al., 2021).

The laws of thermodynamics provide a structure for understanding magnetic energy as it follows the transfer and transformation of these principles as energy moves across Earth's systems. The second law of thermodynamics states that entropy will always increase in an isolated system, quantifying the randomness and disorder. When energy is transferred or transformed, a portion is lost to heat, increasing the system's entropy. So, when a solar event interacts with our planet's magnetosphere, geomagnetic storms induce Joule heating in the ionosphere, particularly at high latitudes, significantly altering atmospheric temperatures and density (Qian et al., 2019). This Joule heating directly results from geomagnetic induced currents, establishing a precise thermodynamic flow during geomagnetic storms and using these fundamentals for interior thermal variations created by interior GICs.

<u>The Geomagnetic Field</u>

Solar events release vast amounts of energy that interact with Earth's magnetosphere, generating geomagnetic storms. These storms propagate within the dynamic system of the Earth's geomagnetic field, generated by the convective motion of the molten iron fluid outer core, a process known as the geodynamo. The motion induces electric currents and magnetic fields through electromagnetic induction, forming a complex system that extends from the outer core into the atmosphere(Glatzmaier & Robertst, 1995). Barenghi (2024) illustrates how complex this system is with the blue field lines pointing inwards and gold field lines pointing outwards (Figure 1). The field lines are tangled within the Earth's core in a turbulent convention that generates a self-sustaining magnetic field.

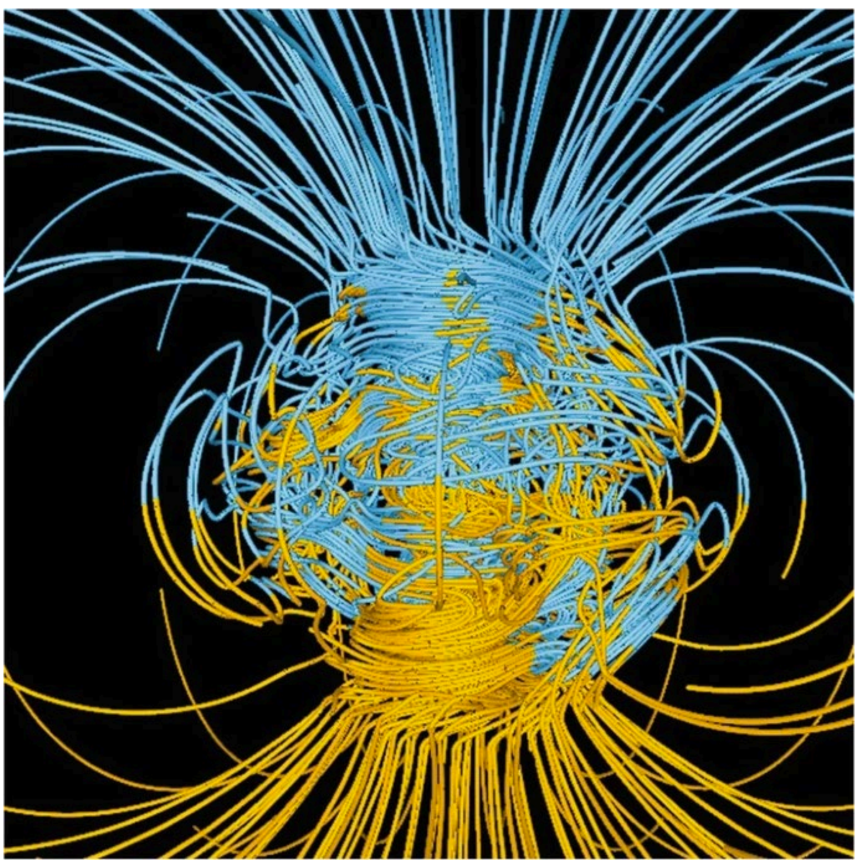

Figure 1 Earth's Magnetic Field Model illustrating Complexity and Tangled Vortex Lines (Barenghi, 2024)

Geomagnetic storms persist for several days, with an extended recovery phase lasting up to a week (Haines et al., 2019). During this phase, energy is redistributed between the magnetosphere, ionosphere, and potentially deeper layers of the Earth. Magnetic reconnection events in the magnetotail release energy into field-aligned currents, which interact with the ionosphere, generating geomagnetic-induced currents (GICs) in the crust and mantle. The GICs concentrate along conductive pathways such as fault zones, producing localized Joule heating (Nakamura et al., 2018).

Auroras, ionospheric heating, and disruptions to surface electrical systems confirm energy redistribution during geomagnetic storms (Qian et al., 2019). The prolonged cycling of geomagnetic energy suggests that, similar to surface processes, it may also influence deeper GICs, observable in regions of high conductivity. For instance, Yellowstone has a high electrical conductivity of an underground plume of partly molten rock feeding into the caldera. Represented in this conductivity map created by the Department of Geology and Geophysics at University of Utah (Figure 2) with high conductivity shown in yellow and red and the significant depths that it reaches on a scale of Yellowstone's size labeled as YNP (*Zhdanov et al.,* 2011). Given its unique geological characteristics, this emphasizes the significance of choosing YNP as the study site for understanding deep geomagnetically induced currents (GICs).

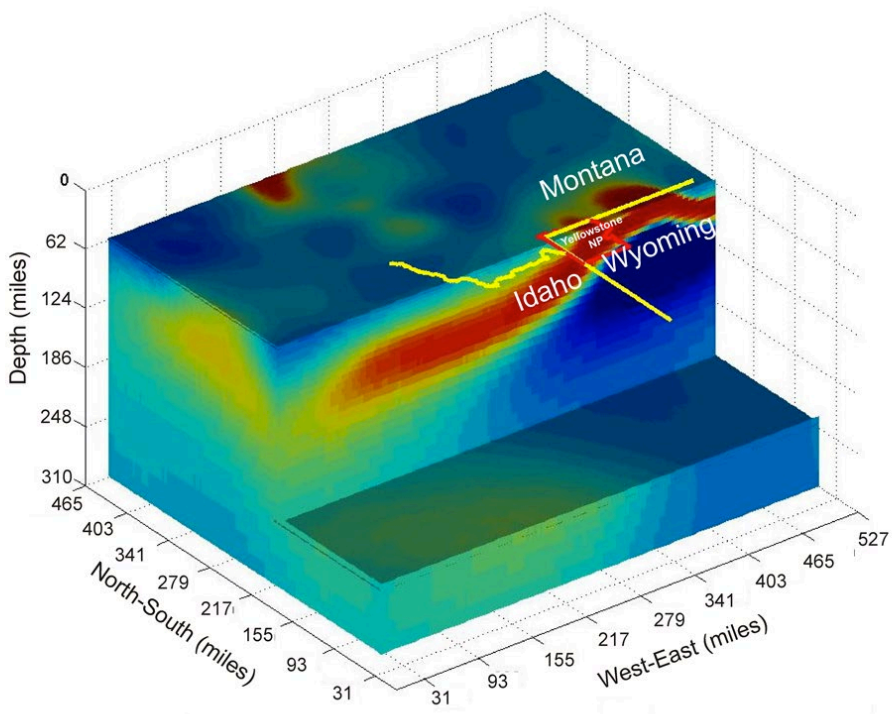

Figure 2 Electrical conductivity and depth of possible GIC locations inducing geothermal features (Zhdanov et al., 2011).

Geomagnetic Storms and Natural Phenomena

In this section, I describe the impact of geomagnetic storms on natural processes; showing reoccurring anomalies in data that can be explained through causality in deeper GICs. In 2020, The National Defense Authorization Act (NDAA) implemented provisions to enhance our understanding of our geomagnetic field and its effect. Research presented the following year on the interactions between geospace and lithospheric processes further supports the notion that geomagnetic activity can influence deep tectonic systems. Ouzounov and Khachikyan (2021) propose that geomagnetic field lines, under certain conditions, may penetrate Earth's surface along fractures and fault lines, potentially impacting lithospheric activity in tectonically active regions (Ouzounov & Khachikyan, 2022). When geomagnetically induced currents are drawn into Earth’s crust along conductive pathways, such as fault lines they present as sporadic, indicating a potential for deeper pathways that present variations further along that path that create GICs within the Earth instead of solely on the surface. Observing illustrations of geomagnetic field lines intersecting (Gvishiani & Soloviev, 2020b) with tectonic fractures, we can hypothesize that areas of heightened crustal conductivity may facilitate the downward flow of geomagnetic energy (Figure 3&4. Ouzounov & Khachikyan, 2021). This study found that geomagnetic storms influence geothermal systems by modulating heat flow and amplifying thermal gradients near geothermal reservoirs (Ouzounov & Khachikyan, 2021, 2022). These surface GICs indicate that geomagnetic influences may shape geothermal dynamics indirectly, especially in regions where geological structures are highly conductive, which again is demonstrated in Yellowstone.

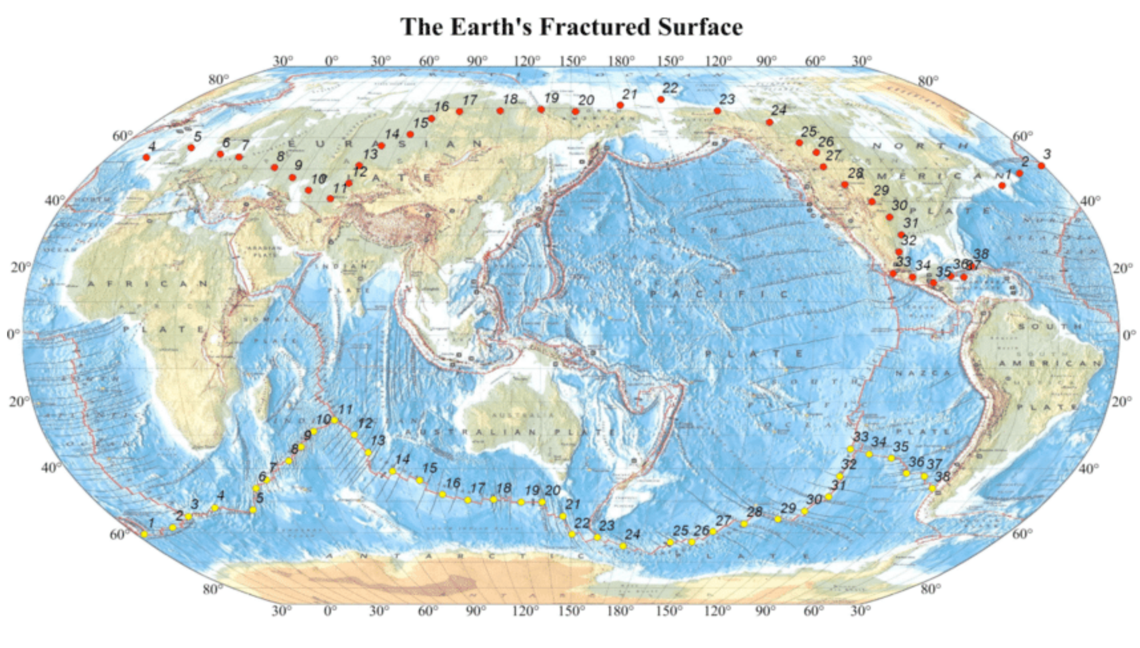

Figure 3 The Earth's highly conductive fractured surface and fault lines (Ouzounov & Khachikyan, 2021)

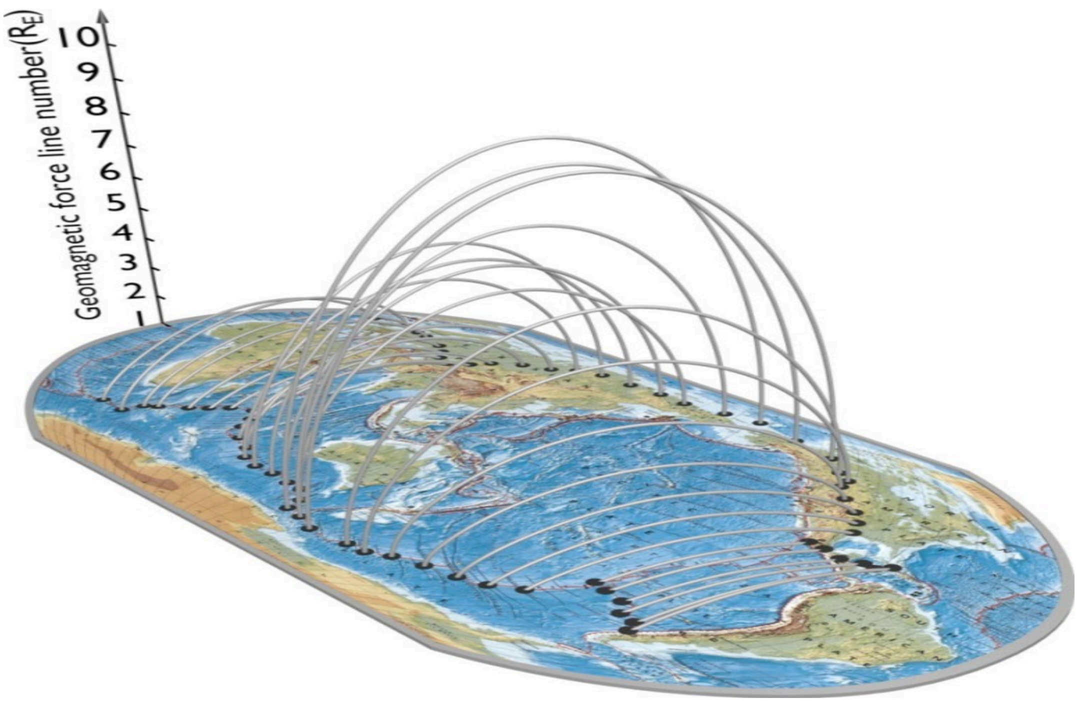

Figure 3 The Earth's highly conductive fractured surface and fault lines (Ouzounov & Khachikyan, 2021)

Hurricane Cycle and Solar Cycle

Observing Ouzounov & Khachikyan (2021) model (Figure 3&4) of the Earth's magnetic field lines, ocean field lines are reviewed briefly here. Mendoza and Pazos (2009), applied spectral analysis to a 22-year hurricane cycle with the sun's solar cycles and used the variation to study how it interacts with the geomagnetic field. The analysis used Dst index variations of the geomagnetic field to track solar cycles and found correlations with the highest hurricanes during the ascending part of odd solar cycles and the descending phase of even solar cycles (Mendoza & Pazos, 2009). The study shows a 22-year cycle of hurricanes with slight variations, with the

Atlantic behaving differently than Pacific hurricanes concerning solar activity, further illustrating how solar activity carries into geomagnetic activity that alters natural processes.

Geomagnetic Storms and Seismic Activity

The U.S. Geological Survey recognizes the connection between geomagnetically induced currents (GICs) and significant impacts on Earth's anthropogenic electrical systems, indicating further investigation into why these exact mechanisms of GICs are also linked to seismic events. A statistical study correlating geomagnetic storms and global earthquakes during 1957-2020 concluded with statistically correlated evidence that more geomagnetic storms occur before global M>7.0 earthquakes (Chen et al., 2020b). The study shows a time series of geomagnetic storms 20 days leading up to significant earthquakes and 20 days after the earthquake (Figure 5), with the middle vertical dotted lines representing M>7.0 or greater earthquakes and horizontal lines representing Dst index with red showing geomagnetic storms.

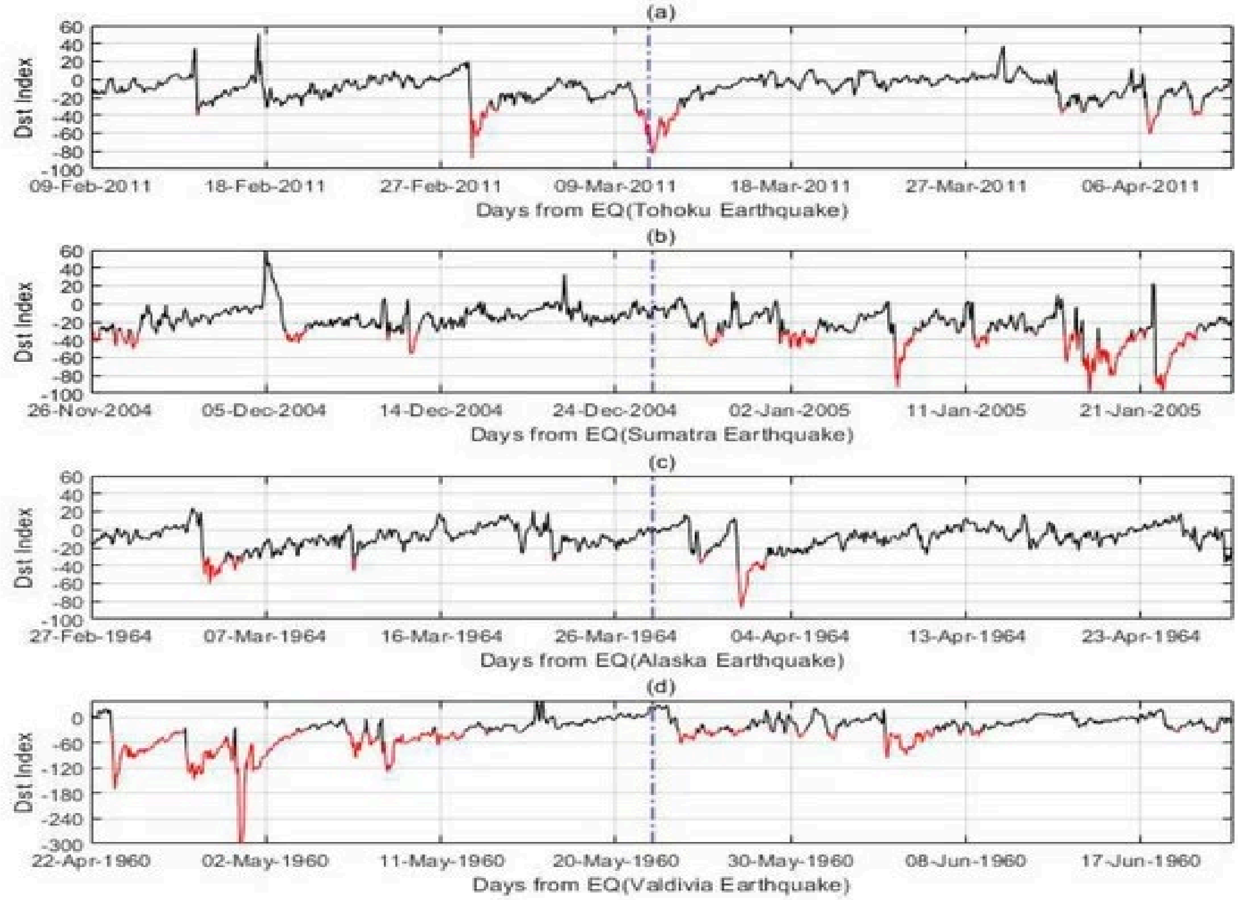

Figure 4 Dst Index correlated with seismic activity events (Chen et al., 2020b)

There are slight variations in the number of geomagnetic storms with seismic activity summarized as potential buildup of tectonic stress until it reaches a critical level to move the tectonic plates (Chen et al., 2020b; Sadhukhan et al., 2021). The study shows correlations through unknown mechanisms, indicating that further research is needed to explore this observation. Looking back at the model of the Earth's magnetic field (Figure 1), we remember the complexity and irregular path of the magnetic field. Studies previously make no mention of tilt or geographical location of field line impact during solar events, giving such a large area for geomagnetic flow. For this proposal, the model explores possible build-up and specific geographical locations of deeper GICs that create these anomalies in correlation data.

Now, to review this correlation, the geomagnetic storms create geomagnetic-induced currents within the mantle and core; with the transfer of energy according to thermodynamics, an increase of entropy is released in the form of Joule heating. Storm variations create electrical currents, which are drawn to highly conductive sites. Once this energy transfer occurs, entropy increases as heat converts into thermal energy that causes rock expansion and compression. This compressing of rock and tectonic plates can be from Joule heat produced by GICs in deeper magma chambers, ultimately triggering seismic activity. This mechanism makes it possible for geomagnetic storms to facilitate interior geological processes that carry to observable ecosystem adaptations. Proposing to calculate this flow of geomagnetic energy into Joule heating through natural processes like geothermal features that would indicate heating instantaneously based on the chemical deposition rate of surrounding mineral rock without advanced technology.

Several studies investigating geothermal and tectonically active regions, such as Iceland and Japan, found correlations between geomagnetic storms and increased geothermal activity (Nakamura et al., 2018) providing preliminary evidence of these interactions. For example, in high geothermal output areas in Iceland, geothermal system pressures and heat flow increased following geomagnetic storm events, suggesting that GICs influence subsurface geothermal conditions (Garrott et al., 2002; Hounslow et al., 2018). Supporting the need for further research into the effects of geomagnetic energy on geothermal reservoirs in tectonically active environments.

Geomagnetic storms, driven by solar events, interact with Earth's magnetosphere, producing geomagnetically induced currents (GICs) within the crust and mantle (Grayver, 2024). These currents create localized heating effects, known as Joule heating, which may influence geothermal systems by increasing crustal temperatures and potentially affecting geothermal reservoirs. Although direct links between geomagnetic activity and geothermal processes are still under investigation, research suggests that GICs in tectonically active areas may affect subsurface thermal environments, contributing to geothermal dynamics in specific regions (Love & Swidinsky, 2014).

I hypothesize that Yellowstone's geomagnetic activity has a pronounced effect on geothermal systems due to the region's high geothermal gradient and active fault structures. Heat and mineral flux from Yellowstone's geothermal features may be modulated by geomagnetically induced currents (GICs) in magma chambers and fault lines, which act as pathways for magnetic energy transfer into thermal energy.

Geothermal Heat in Yellowstone National Park

Yellowstone National Park (YNP) is the oldest and one of the largest national parks in northwestern Wyoming, part of southern Montana and eastern Idaho. YNP is known for its highly active and diverse geothermal and hydrologic features (Vaughan et al., 2020), including geysers, hot springs, fumaroles, and mud pots. The importance of this location lies in the various natural ecological processes within the park that are less subjected to human alterations, focusing on understanding natural flows of ecosystem adaptations. The purpose of this system is to provide another possible avenue of causality of ecosystem adaptations and the ability to refer to the flow of geological thermodynamics.

The geothermal features are fueled by subsurface heat from the magma chamber under Yellowstone Caldera. It is sustained by the underlying volcanic system with shallow magma chambers beneath the Caldera consisting of primarily molten and semi-molten rock, generating substantial geothermal energy (Hurwitz & Lowenstern, 2014). Given its high conductivity, geothermal energy rises to the surface through fractures and fault lines. Geysers, hot springs, fumaroles, and mud pots are heated through Joule heating from deep magma chambers below. Rhyolitic rock that overlays within the system influences geothermal dynamics and has a high silica content, making it a poor conductor of heat (Finn et al., 2022). Instead, it traps geothermal energy within the crust until localized intense heat buildup, contributing to heat accumulations and escaping through these known geothermal features. Finn (2022) illustrates this in a geological map (Figure 7), representing the rhyolite in pink that overlays the YNP caldera in grey boundary line.

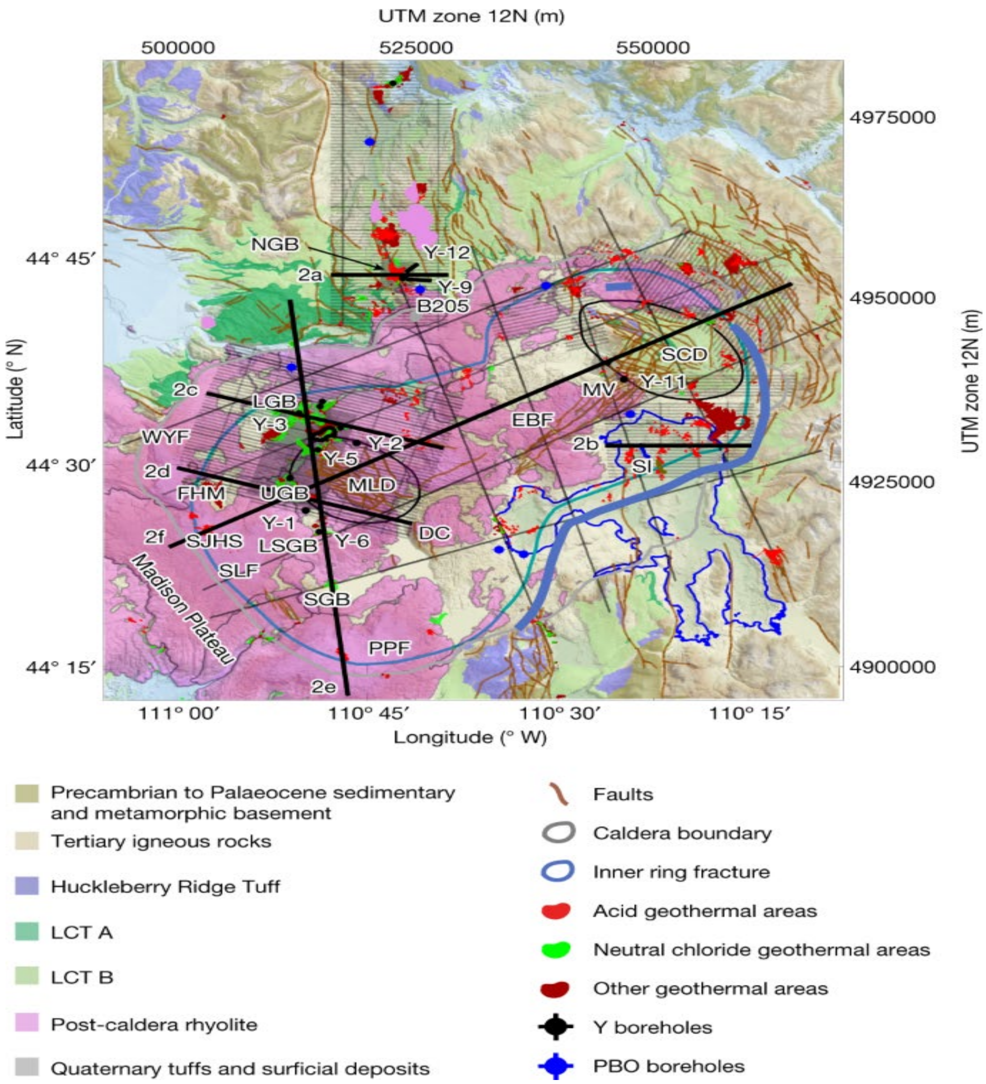

Figure 5 Yellowstone's geological map representing the rhyolite overlay that forms the geothermal pockets in Yellowstone (Finn et al., 2022)

Rhyolite creates high silica content in hot springs; as the water circulates through rhyolite, it dissolves silica, sulfur, and calcium with various trace elements that create Yellowstone's thermal waters. This rock dissolution slows upward heat flow to influence mineral composition and thermal distribution between subsurface geology and surface ecosystems (Hurwitz & Lowenstern, 2014). Rhyolite aids in data collection to correlate mineral composition rate with thermal build-up with geomagnetic storms to verify causality in geothermal variations.

Geothermal heat from magma chambers has numerous influences on Yellowstone's ecosystem, altering soil composition, water availability, and vegetation patterns (Fournier, 1989).

Geothermal features influence surrounding environments by shaping vegetation patterns, soil composition, and water chemistry, creating microhabitats (Gao, 2024; Zuo et al., 2023). Microhabitats will utilize heat-tolerant plant species and thriving microbial communities (Stout & Al-Niemi, 2002). Geothermal heat from hot springs and fumaroles creates greater soil temperatures in localized areas that alter soil composition and nutrient cycling. Requiring heat-tolerant plant species like Yellowstone sand verbena (*Abronia ammonphila*), hot spring phlox *(Phlox kelseyi)*, douglas sedge *(Carex douglasii)* and tufted hairgrass *(Deschampsia cespitosa)* are typical near geothermal areas that have adapted to warmer soil temperatures with specific roots that absorb mineral-rich waters found having increased biomass penetrating deeper soil layers. This is also true with lodgepole pine (*Pinus contorta*) resilience to increased soil temperatures (Clark et al., 2017) and fire regimes across Yellowstone. Lodgepole pine resilience can also be explained by constant seismic shifts from thermal build-up that create tiny fissures in dry climates, increasing water availability (Fournier, 1989; Gao, 2024). Vegetation penetrating deeper soil layers access high sulfur and mineral content, influencing sulfur and nitrogen nutrient cycling within the ecosystem (Fournier, 1989; Parmenter et al., 2003). Along with soil composition shifts, mineral deposition from rhyolitic rock dissolving silica, sulfur, calcium, and trace elements creates mineral-rich soils (Hurwitz & Lowenstern, 2014). This geothermal activity creates sulfur deposits near fumaroles and silica precipitation near hot springs that provide nutrients for thermophilic bacteria and vegetation, tolerating high levels of dissolved minerals (Stout & Al-Niemi, 2002).

The chemical composition of geothermal waters also affects aquatic ecosystems. These geothermal waters create variations in water temperature, pH, and mineral content, creating habitats for thermophilic microorganisms and influencing the distribution of aquatic species (Gonzalez et al., 2018). The high silica content found in hot springs supports the growth of specific microbial mats, contributing further to geological thermodynamic flow within the ecosystem through nutrient cycling.

The geothermal features in Yellowstone contribute to a more extensive, diverse ecological system between soil chemistry, plant adaptation, and microbial diversity. These features create microhabitats with high soil temperatures and mineral content, generating specialized plant species and microbial communities that only thrive in these challenging conditions. Deposing dissolved rhyolitic rock minerals facilitates thermophilic organisms that are also significant in this ecosystem’s reliance and nutrient flow (Hurwitz & Lowenstern, 2014; Stout, & AL-Niemi, 2002). Consequently, Yellowstone’s geothermal processes contribute to natural energy flows, facilitating localized ecological changes that contribute to the park’s environmental patterns. These geothermal and plant adaptations and microbial activity processes highlight the significance of understanding the flow of geological thermodynamics as it shapes ecological adaptations. Confirming this concentrated area of geological thermodynamics impacting microhabitat adaptations further reiterates the importance of deep GICs throughout, on a planetarium scale, from a single geothermal feature, how vast these solar events are impacting our Earth.

CHAPTER THREE

SOLAR EVENTS AS A DRIVER OF GEOTHERMAL VARIABILITY

Yellowstone's Geothermal Features

Yellowstone's geothermal features are shaped by deep subsurface processes and influenced by multiple natural energy flows. I present in this section presents a conceptual model hypothesizing causality through deep geomagnetically induced currents (GICs) indirectly influencing Yellowstone's geothermal systems by altering heat distribution within the mantle and crust. Although direct testing of deep GICs is unavailable due to the lack of technology at this depth, the model provides a framework to introduce a natural driver of ecological adaptations, giving another avenue of causality.

Mechanism of Causality

Solar events, such as solar flares and coronal mass ejections (CMEs), send bursts of electromagnetic energy into Earth's magnetosphere, creating geomagnetic storms that propagate through the geomagnetic field (Syed Zafar et al., 2021). Geomagnetic storms potentially induce electric currents within the Earth's crust and mantle, particularly along conductive pathways like fault lines. Geomagnetically induced currents (GICs) generate heat through Joule heating as electrical resistance converts electric energy into thermal energy(Fujiwara et al., 2023). Yellowstone is a tectonically active area; induced heating can lead to localized changes in geothermal reservoirs, affecting features like geysers, hot springs, and fumaroles.

Proposed Study

My study proposes that solar events induce deep GICs throughout the intrinsic geomagnetic field path, contributing to geological adaptations and natural phenomena. Through geothermal activity, I want to confirm these deep currents by rock dissolution rates in geothermal waters, bypassing advanced technology. Peaks in solar cycles with increased solar events coincide with heightened geomagnetic disturbance (Syed Zafar et al., 2021), leading to stronger GICs transferred in Earth's interior crust and mantle. Following this system, as it moves into ecological processes from joule, heating creates significant disorder at this stage. As the currents cycle within Yellowstone's tectonic structures, we can utilize the influence of thermal gradients, increase subsurface pressures, and alter the behavior of geothermal features as a potential step in energy transfer to follow the disorder. My study provides a plausible explanation for some of the geothermal variability observed in YNP, laying the groundwork for future empirical testing.

THEORETICAL FRAMEWORK

My theoretical framework aims to visualize and quantify the flow of geomagnetic energy from solar-driven geomagnetic storms to deep GICs and their subsequent influence on Yellowstone's geothermal features.

The model will incorporate the following components:

Data Integration: Collecting high-resolution magnetotelluric (MT) data and comprehensive geomagnetic indices such as the Dst index and field variation measurements at to establish baseline energy flow patterns in Yellowstone. Exact ground field variations are collected as well with the closest site to YNP being (BOU) Boulder, Colorado observatory site. This will include integrating data on orientation of the Earth during solar event impact, the duration of geomagnetic storm cycles, and variations in the geomagnetic field. The data will provide a multidimensional context for understanding how surface-level energy changes connect to deeper GIC processes and how these geomagnetic disturbances potentially induce deep currents propagating through the crust and mantle.

Geothermal Deposition Analysis: Correlate the continuous monitoring of both deposition and dissolution rates of silica, calcium carbonate, and other specific minerals in geothermal waters, which vary with different heat rates, along with the intensity and timing of geomagnetic storms. The dissolution rate of chemicals within the water can be estimated using the Arrhenius equation for dissolution. This approach provides a version of how dissolution rates might work, considering the variations in types of rhyolite and heat gradients present in Yellowstone:

Table 1 Arrhenius Equation for Dissolution Rate

Arrhenius Equation for dissolution	
$$D = ke = -\frac{E_a}{RT}$$	
D	Dissolution rate (mol/m²/s)
k	Pre-exponential factor (characteristics of rock)
E_a	Activation energy (J/mol)
R	Universal gas constant (8.314 J/ mol·K)
T	Temperature in Kelvin (K)

(*6.2.3.1*, 2013)

The dissolution rate of chemicals within the water indicates specific heat levels generated, including those influenced by Joule heating from deep GICs. Table. 2 illustrates an estimated relationship between temperature and the dissolution rate of rhyolite rock, alongside the corresponding increase in silica concentration in geothermal waters. These estimates reflect general trends, acknowledging that different types of rhyolite and temperature variations within the geothermal gradient may affect the specific dissolution rates.

Table 2 Silica Concentration with Temperature Variations

Temperature (K)	Dissolution Rate (mol/m¬≤/s)	Silica Concentration Increase in Water (mg/L)
423.15	3.92E-14	3.92E-15
473.15	2.38E-13	2.38E-14
523.15	1.02E-12	1.02E-13
573.15	3.40E-12	3.40E-13

Dissolution characteristics are collected with In Situ Ultraviolet Spectrophotometer (ISUS)(*UCSD*,2023) . Data collected will also be correlated with solar events' tilt and impact angle, as the resulting geomagnetic field lines may cycle and concentrate energy in specific areas. This would act as a proxy for confirming deep GIC activity and understanding their effects on geothermal variability.

Thermal Gradient and Pressure Influence: Model the effects of GIC-induced Joule heating as it interacts with thermal gradients with resistance temperature detector (RTD) (Dames, 2008) and subsurface pressures within tectonic structures. This interaction leads to observable changes in geothermal features, seen in variations of geyser activity and hot spring temperatures, providing a clear correlation between geomagnetic activity and geothermal dynamics.

Implementation of Theoretical Framework: Extend the model to explore how changes in geothermal activity, driven by deep GICs, impact their surrounding ecosystem. Based on current research on geothermal ecosystems, my framework aims to predict occurrences of magnetic energy shifts to resource in species resilience, vegetation patterns, microbial community variations and any ecosystem change driven by soil and precipitation chemistry compositions. This will help identify potential correlations between magnetic energy cycling and ecosystem changes in Yellowstone, providing causality into the mechanisms possibly driving their ecosystem dynamics. The potential of predicting magnetic energy shifts facilitating geothermal activity allows researchers the ability for control and experimental groups in the field.

By using Yellowstone to link the magnetosphere, mantle, and surface, this region can be a conservative natural site for determining the connections between solar-driven geomagnetic energy and Earth's interior processes. The potential of this study can also contribute to understanding the planetary scale of the geomagnetic field and the role of deep GICs in bridging gaps in our current knowledge of natural phenomena. These deep GICs can fill the gap in correlating geomagnetic energy with many natural processes, including seismic activity, hurricanes, volcanic activity, and geothermal dynamics. Anomalies in correlation data hypothesize energy build-up. However, my study suggests that deep GICs are also the potential underlying factor creating these correlations across various natural phenomena, aiding in a comprehensive understanding of geothermal ecosystem variations driven by solar-induced geomagnetic energy.

LIMITATIONS

The primary limitation of this model is the accuracy of the Dst index, a broad differential measurement that reflects overall changes in Earth's magnetic field strength during geomagnetic disturbances. The Dst index is continuously monitored using data from several observatories worldwide that provide an average measure of global geomagnetic variations. However, specific monitoring of the geomagnetic field at ground level is limited to a relatively small number of observatories across the globe. For Yellowstone, the closest geomagnetic observatory is located in Boulder, Colorado. While Boulder is relatively close on a planetary scale, it still presents limitations when performing precise analyses of geomagnetic field line interactions in this region.

The analysis of geomagnetic storm impacts using data from observatories from Boulder (USA), Kakioka (Japan), and San Juan (USA) on March 23-24, 2023, illustrating spatial and temporal variations (Figure 7,8&9). These observatories show differences in the hour and day of the geomagnetic impact, showing the possible limitation of not having a direct monitoring site at YNP. For example, while the event was significant in Japan, it impacted at a different time and duration compared to the observations in Boulder and San Juan, demonstrating how geomagnetic effects can vary both spatially and temporally. The variation of impact seen with San Juan compared to Boulder is slight, whereas the impact was seen first in Japan.

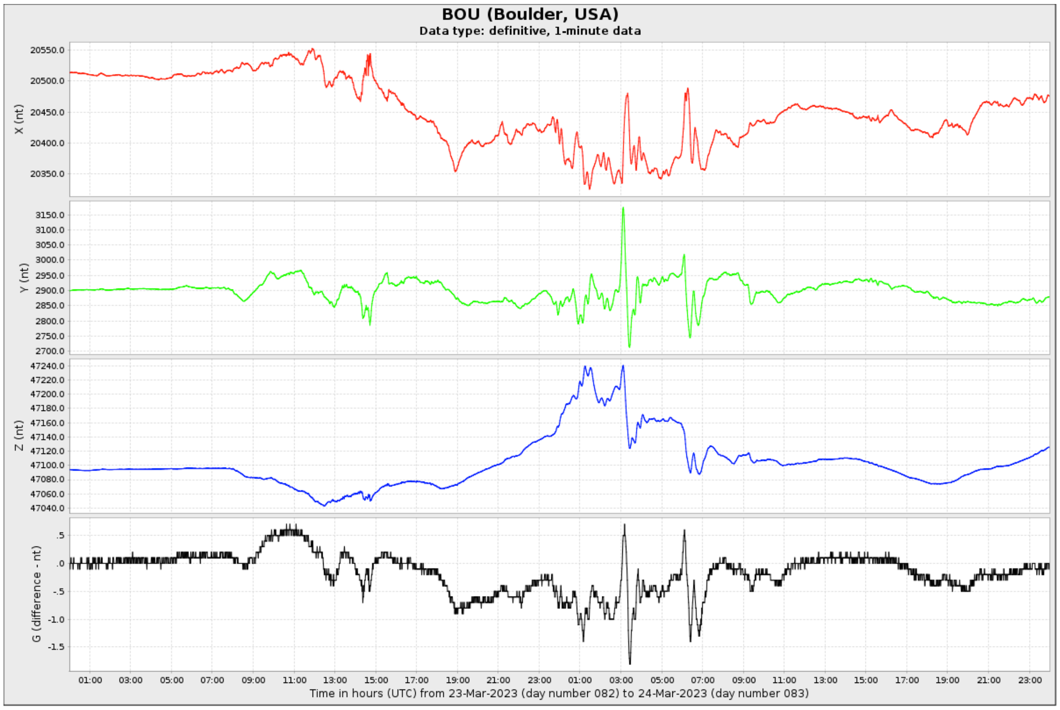

Figure 6 Boulder, Colorado Field Variations at Observatory BOU on 03/23/2023 (INTERMAGNET Data Viewer, 2023)

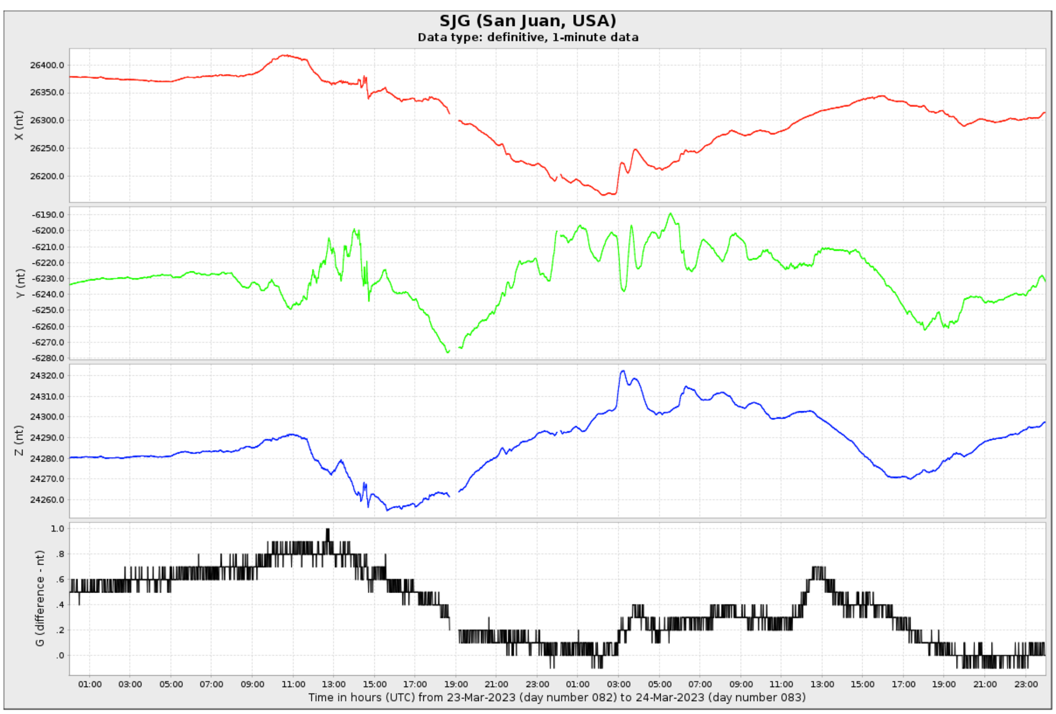

Figure 7 San Juan, California Field Variations at Observatory SJG on 03/23/2023 (INTERMAGNET Data Viewer, 2023)

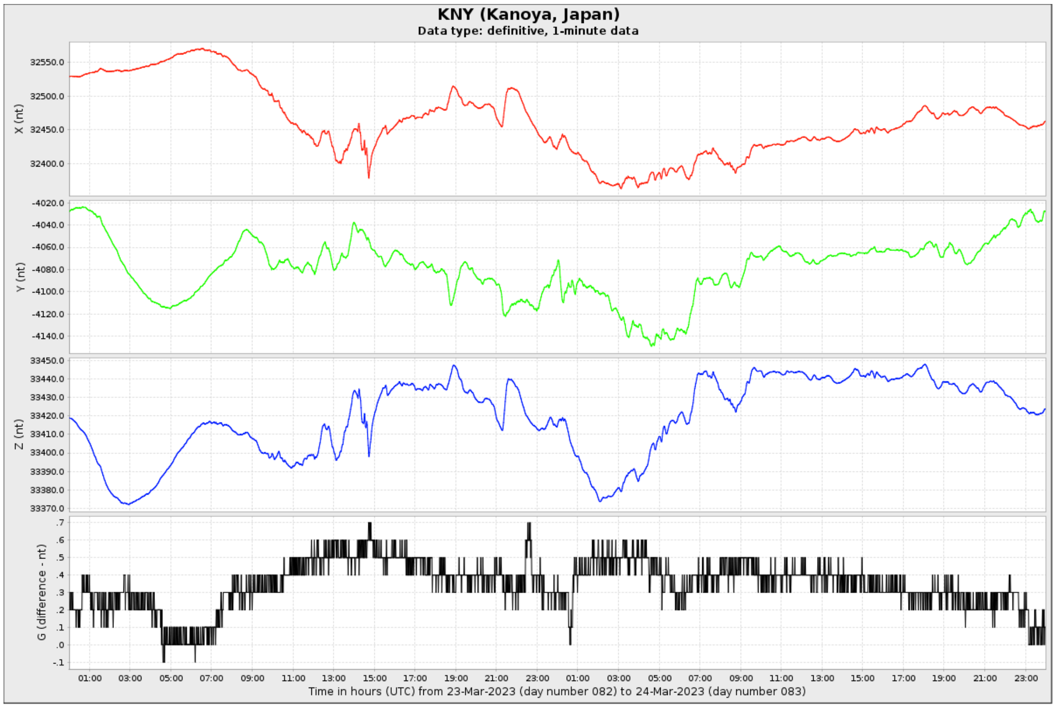

Figure 8 Kanoya, Japan Field Variations at Observatory (KNY) on 03/23/2023 (INTERMAGNET Data Viewer, 2023)

We see the importance of observing geomagnetic storms from exact and multiple locations to understand their temporal and spatial dynamics fully. It also highlights the need for more geographically specific observations, particularly given the significance of factors like the tilt of Earth's magnetic field, the timing of the solar event, and the specific location of impact.

Establishing more dedicated geomagnetic monitoring sites would significantly enhance our ability to observe planetary scale geomagnetically induced current (GIC) movements and their influence on surrounding ecosystems. The transfer of magnetic energy into thermal energy alters the geochemistry of geothermal waters, which in turn impacts the chemical composition of soil and precipitation. These geochemical shifts influence species-specific resilience and vulnerability (Rinehart, 1980). Variations in geochemistry affect multiple aspects of the ecosystem, including fungal community growth and vegetation patterns, as well as the growth, resilience, and adaptive capacity of species that rely on specific soil chemical compositions (Bazzicalupo et al., 2021; Channing & Edwards, 2009). Magnetic energy driving changes in geochemistry, facilitates ecosystem shifts, altering vegetation patterns and microbial community growth, shifting the ecosystem dynamics of the surrounding area.

CONCLUSION

My study presents a conceptual model that reframes solar events as drivers of geological thermodynamics through a geomagnetic energy flow extending from the magnetosphere to the Earth's interior. In the model, geomagnetic storms create geomagnetically induced currents (GICs) that cycle through the outer core, where variations in the geomagnetic field create deep GICs throughout different areas of the field path, leading to variations in depth and impact within the Earth's interior.

Using geomagnetic, geothermal, rock dissolution, and thermal dynamics, my proposed study enables a more comprehensive visualization of geological thermodynamic pathways, including transferring heat from solar events to terrestrial systems. We gain insights into the causality of geothermal ecosystem through rock dissolution rates induced by thermal energy. Furthermore, using YNP’s highly conductive geological features to track deep GICs, as it offers a natural undeveloped area to correlate these relationships.

Future research should focus on refining this model through empirical testing, incorporating more localized data from additional observation sites to address current limitations.

Establishing direct monitoring in regions like Yellowstone will enhance the accuracy of understanding how solar-driven geomagnetic energy cycles influence geological and ecological processes at varying depths. Ultimately, this study lays the foundation for exploring how solar events influence Earth's internal dynamics, contributing to a broader comprehension of planetary energy flow and its implications for natural systems.

REFERENCES CITED

6.2.3.1: Arrhenius Equation. (2013, October 2). Chemistry LibreTexts. https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Kinetics/06%3A_Modeling_Reaction_Kinetics/6.02%3A_Temperature_Dependence_of_Reaction_Rates/6.2.03%3A_The_Arrhenius_Law/6.2.3.01%3A_Arrhenius_Equation

Ball, J. W., McCleskey, R. B., Nordstrom, D. K., Holloway, J. M., & Sturtevant, S. A. (2002). *Water-Chemistry Data for Selected Springs, Geysers, and Streams in Yellowstone National Park, Wyoming, 1999-2000*.

Bazzicalupo, A. L., Erlandson, S., Branine, M., Ratz, M., Ruffing, L., Nguyen, N. H., & Branco, S. (2021). *Fungal community turnover along steep environmental gradients from geothermal soils in Yellowstone National Park* (p. 2021.04.06.438641). bioRxiv. https://doi.org/10.1101/2021.04.06.438641

Buotte, P. C., Hicke, J. A., Preisler, H. K., Abatzoglou, J. T., Raffa, K. F., & Logan, J. A. (2016). Climate influences on whitebark pine mortality from mountain pine beetle in the Greater Yellowstone Ecosystem. *Ecological Applications*, *26*(8), 2507–2524. https://doi.org/10.1002/eap.1396

Channing, A., & Edwards, D. (2009). Yellowstone hot spring environments and the palaeo-ecophysiology of Rhynie chert plants: Towards a synthesis. *Plant Ecology & Diversity*. https://doi.org/10.1080/17550870903349359

Chen, H., Wang, R., Miao, M., Liu, X., Ma, Y., Hattori, K., & Han, P. (2020a). A Statistical Study of the Correlation between Geomagnetic Storms and M ≥ 7.0 Global Earthquakes during 1957–2020. *Entropy*, *22*(11), Article 11. https://doi.org/10.3390/e22111270

Chen, H., Wang, R., Miao, M., Liu, X., Ma, Y., Hattori, K., & Han, P. (2020b). A Statistical Study of the Correlation between Geomagnetic Storms and M ≥ 7.0 Global Earthquakes during 1957–2020. *Entropy*, *22*, 1270. https://doi.org/10.3390/e22111270

Clark, J. A., Loehman, R. A., & Keane, R. E. (2017). Climate changes and wildfire alter vegetation of Yellowstone National Park, but forest cover persists. *Ecosphere*, *8*(1), e01636. https://doi.org/10.1002/ecs2.1636

Dames, C. (2008). Resistance Temperature Detectors. In D. Li (Ed.), *Encyclopedia of Microfluidics and Nanofluidics* (pp. 1782–1790). Springer US. https://doi.org/10.1007/978-0-387-48998-8_1354

Finn, C. A., Bedrosian, P. A., Holbrook, W. S., Auken, E., Bloss, B. R., & Crosbie, J. (2022). Geophysical imaging of the Yellowstone hydrothermal plumbing system. *Nature*, *603*(7902), 643–647. https://doi.org/10.1038/s41586-021-04379-1

Fournier, R. O. (1989). Geochemistry and Dynamics of the Yellowstone National Park Hydrothermal System. *Annual Review of Earth and Planetary Sciences*, *17*(Volume 17, 1989), 13–53. https://doi.org/10.1146/annurev.ea.17.050189.000305

Fujiwara, H., Miyoshi, Y., & Jin, H. (2023). Effects of Solar Activity on the Upper Atmosphere. In K. Kusano (Ed.), *Solar-Terrestrial Environmental Prediction* (pp. 421–444). Springer Nature. https://doi.org/10.1007/978-981-19-7765-7_14

Gao, S. (2024, February 10). *Shifts of forest resilience after seismic disturbances in tectonically active regions | Nature Geoscience*. Nature Geoscience. https://www.nature.com/articles/s41561-024-01380-x

Garrott, R. A., Eberhardt, L. L., Otton, J. K., White, P. J., & Chaffee, M. A. (2002). A Geochemical Trophic Cascade in Yellowstone's Geothermal Environments. *Ecosystems*, *5*(7), 0659–0666. https://doi.org/10.1007/s10021-002-0211-8

Glatzmaier, G. A., & Robertst, P. H. (1995). *A three-dimensional self-consistent computer simulation of a geomagnetic field reversal*. *377*.

Gonzalez, P., Wang, F., Notaro, M., Vimont, D. J., & Williams, J. W. (2018). Disproportionate magnitude of climate change in United States national parks. *Environmental Research Letters*, *13*(10), 104001. https://doi.org/10.1088/1748-9326/aade09

Grayver, A. (2024). Unravelling the Electrical Conductivity of Earth and Planets. *Surveys in Geophysics*, *45*(1), 187–238. https://doi.org/10.1007/s10712-023-09813-9

Gvishiani, A., & Soloviev, A. (2020a). Structure of the Earth's Magnetic Field. In A. Gvishiani & A. Soloviev (Eds.), *Observations, Modeling and Systems Analysis in Geomagnetic Data Interpretation* (pp. 1–27). Springer International Publishing. https://doi.org/10.1007/978-3-030-58969-1_1

Gvishiani, A., & Soloviev, A. (2020b). Structure of the Earth's Magnetic Field. In A. Gvishiani & A. Soloviev, *Observations, Modeling and Systems Analysis in Geomagnetic Data Interpretation* (pp. 1–27). Springer International Publishing. https://doi.org/10.1007/978-3-030-58969-1_1

Haines, C., Owens, M. J., Barnard, L., Lockwood, M., & Ruffenach, A. (2019). The Variation of Geomagnetic Storm Duration with Intensity. *Solar Physics*, *294*(11), 154. https://doi.org/10.1007/s11207-019-1546-z

Hounslow, M. W., Domeier, M., & Biggin, A. J. (2018). Subduction flux modulates the geomagnetic polarity reversal rate. *Tectonophysics*, *742–743*, 34–49. https://doi.org/10.1016/j.tecto.2018.05.018

Hurwitz, S., & Lowenstern, J. B. (2014). Dynamics of the Yellowstone hydrothermal system. *Reviews of Geophysics*, *52*(3), 375–411. https://doi.org/10.1002/2014RG000452

INTERMAGNET Data Viewer. (2023, March 23). INTERMAGNET. https://imag-data.bgs.ac.uk/GIN_V1/GINForms2?observatoryIagaCode=BOU&publicationState=Best+available&dataStartDate=2023-03-23&dataDuration=2&samplesPerDay=minute&submitValue=View+%2F+Download&request=DataView

Juusola, L., Vanhamäki, H., Viljanen, A., & Smirnov, M. (2020). Induced currents due to 3D ground conductivity play a major role in the interpretation of geomagnetic variations. *Annales Geophysicae*, *38*(5), 983–998. https://doi.org/10.5194/angeo-38-983-2020

Kono, M., & Roberts, P. H. (2002). RECENT GEODYNAMO SIMULATIONS AND OBSERVATIONS OF THE GEOMAGNETIC FIELD. *Reviews of Geophysics*, *40*(4). https://doi.org/10.1029/2000RG000102

Love, J. J., & Swidinsky, A. (2014). Time causal operational estimation of electric fields induced in the Earth’s lithosphere during magnetic storms. *Geophysical Research Letters*, *41*(7), 2266–2274. https://doi.org/10.1002/2014GL059568

Lowes, F. (2007). Geomagnetic Dipole Field. In D. Gubbins & E. Herrero-Bervera (Eds.), *Encyclopedia of Geomagnetism and Paleomagnetism* (pp. 310–311). Springer Netherlands. https://doi.org/10.1007/978-1-4020-4423-6_114

Mendoza, B., & Pazos, M. (2009). A 22 yr hurricane cycle and its relation with geomagnetic activity. *Journal of Atmospheric and Solar-Terrestrial Physics*, *71*(17), 2047–2054. https://doi.org/10.1016/j.jastp.2009.09.012

Milan, S. E., Clausen, L. B. N., Coxon, J. C., Carter, J. A., Walach, M.-T., Laundal, K., Østgaard, N., Tenfjord, P., Reistad, J., Snekvik, K., Korth, H., & Anderson, B. J. (2017). Overview of Solar Wind–Magnetosphere–Ionosphere–Atmosphere Coupling and the Generation of Magnetospheric Currents. *Space Science Reviews*, *206*(1), 547–573. https://doi.org/10.1007/s11214-017-0333-0

Monitoring Earthquakes in Yellowstone National Park | U.S. Geological Survey. (2023). USGS. https://www.usgs.gov/volcanoes/yellowstone/science/monitoring-earthquakes-yellowstone-national-park?utm_source=chatgpt.com

Monitoring Geothermal Systems and Hydrothermal Features (U.S. National Park Service). (n.d.). Retrieved November 19, 2024, from https://www.nps.gov/articles/geothermal-systems-and-monitoring-hydrothermal-features.htm

Nakamura, S., Ebihara, Y., Fujita, S., Goto, T., Yamada, N., Watari, S., & Omura, Y. (2018). Time Domain Simulation of Geomagnetically Induced Current (GIC) Flowing in 500-kV Power Grid in Japan Including a Three-Dimensional Ground Inhomogeneity. *Space Weather*, *16*(12), 1946–1959. https://doi.org/10.1029/2018SW002004

Ouzounov, D., & Khachikyan, G. (2021). *On the impact of the geospace environment on lithospheric processes*. https://doi.org/10.48550/arXiv.2108.13788

Ouzounov, D., & Khachikyan, G. (2022). *On the impact of the geospace environment on solar-lithosphere coupling and earthquake occurrence* (No. arXiv:2108.13788). arXiv. http://arxiv.org/abs/2108.13788

Parmenter, A. W., Hansen, A., Kennedy, R. E., Cohen, W., Langner, U., Lawrence, R., Maxwell, B., Gallant, A., & Aspinall, R. (2003). Land Use and Land Cover Change in the Greater Yellowstone Ecosystem: 1975–1995. *Ecological Applications*, *13*(3), 687–703. https://doi.org/10.1890/1051-0761(2003)013[0687:LUALCC]2.0.CO;2

Qian, L., Wang, W., Burns, A. G., Chamberlin, P. C., Coster, A., Zhang, S.-R., & Solomon, S. C. (2019). Solar Flare and Geomagnetic Storm Effects on the Thermosphere and Ionosphere During 6–11 September 2017. *Journal of Geophysical Research: Space Physics*, *124*(3), 2298–2311. https://doi.org/10.1029/2018JA026175

Rinehart, J. S. (1980). Chemistry of Geothermal Waters. In J. S. Rinehart, *Geysers and Geothermal Energy* (pp. 92–108). Springer New York. https://doi.org/10.1007/978-1-4612-6084-4_5

Robinson, R. M., & Zanetti, L. J. (2021). Auroral Energy Flux and Joule Heating Derived From Global Maps of Field-Aligned Currents. *Geophysical Research Letters*, *48*(7), e2020GL091527. https://doi.org/10.1029/2020GL091527

Sadhukhan, B., Mukherjee, S., Sarkar, D., & Samanta, R. K. (2021). Investigating the relationship between earthquake occurrences and global temperature fluctuation patterns.

Arabian Journal of Geosciences, *14*(18), 1932. https://doi.org/10.1007/s12517-021-08296-5

Stout, R. G., & Al-Niemi, T. S. (2002). Heat-tolerant flowering plants of active geothermal areas in Yellowstone National Park. *Annals of Botany*, *90*(2), 259–267. https://doi.org/10.1093/aob/mcf174

Stout, R. G., & AL-Niemi, T. S. (2002). Heat-tolerant Flowering Plants of Active Geothermal Areas in Yellowstone National Park. *Annals of Botany*, *90*(2), 259–267. https://doi.org/10.1093/aob/mcf174

Syed Zafar, S. N. A., Umar, R., Sabri, N. H., Jusoh, M. H., Dagang, A. N., & Yoshikawa, A. (2021). Effects of solar flares and coronal mass ejections on Earth's horizontal magnetic field and solar wind parameters during the minimum solar cycle 24. *Monthly Notices of the Royal Astronomical Society*, *504*(3), 3812–3822. https://doi.org/10.1093/mnras/stab1161

Tracking Changes in Yellowstone's Restless Volcanic System | USGS Fact Sheet 100-03. (n.d.). USGS. Retrieved November 23, 2024, from https://pubs.usgs.gov/fs/fs100-03/?utm_source=chatgpt.com

Tyagi, A., Sajad, A., & Park, S. (2023, October 25). *Deciphering the role of mechanosensitive channels in plant root biology: Perception, signaling, and adaptive responses | Planta*. https://link.springer.com/article/10.1007/s00425-023-04261-6

UCSD. (2023). *Nitrate Sensor – In Situ Ultraviolet Spectrophotometer (ISUS) – California Current Ecosystem*. https://ccelter.ucsd.edu/nitrate-sensor-in-situ-ultraviolet-spectrophotometer-isus/

Vaughan, R. G., Hungerford, J. D. G., & Keller, W. (2020). A Newly Emerging Thermal Area in Yellowstone. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.00204

Viterito, A. (2016). The Correlation of Seismic Activity and Recent Global Warming. *Journal of Earth Science & Climatic Change*, *07*(04). https://doi.org/10.4172/2157-7617.1000345

Zhdanov, M., & Smith, R. (2011). *Yellowstone's electrical conductivity hints volcano plume is bigger than thought*. AGU Newsroom. http://sites.agu.org/newsroom/press-release/yellowstones-electrical-conductivity-hints-volcano-plume-is-bigger-than-thought/

Zuo, H., Shen, H., Dong, S., Wu, S., He, F., Zhang, R., Wang, Z., Shi, H., Hao, X., Tan, Y., Ma, C., Li, S., Liu, Y., Zhang, F., & Xiao, J. (2023). Potential short-term effects of earthquake on the plant–soil interface in alpine grassland of the Qinghai–Tibetan Plateau. *Frontiers in Plant Science*, *14*. https://doi.org/10.3389/fpls.2023.1240719