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Unveiling Antarctica's Heat: A Review of Geothermal Heat Flow Estimation and the Rise of Machine Learning

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Abstract: *Antarctica, characterized by its extreme environment and sparse data availability, presents a formidable challenge for estimating geothermal heat flow, a key parameter influencing its geological and glaciological processes. This review paper analyzes existing literature surveys on predicting geothermal heat flow in Antarctica, focusing on various methodologies employed, data sources utilized, and challenges encountered. Highlight the transition from traditional techniques reliant on sparse direct measurements to adopting machine learning (ML) approaches leveraging diverse datasets. The review synthesizes insights from studies utilizing geological, geophysical, and remote sensing data, alongside advancements in ML algorithms, to improve the spatial resolution and accuracy of heat flow predictions. Through a comprehensive examination of the literature, identify key trends, knowledge gaps, and future directions for research in this critical domain.*

Keywords: component, formatting, style, styling, insert

I. INTRODUCTION

With its vast ice sheets and extreme environmental conditions, Antarctica presents a unique challenge for geoscientists seeking to understand its underlying geological processes. Among these processes, geothermal heat flow is crucial in shaping the continent's dynamics, influencing ice sheet behavior, and providing insights into its tectonic evolution. Accurate estimation of geothermal heat flow is essential for various applications, including climate modeling, glaciology, and resource exploration. Traditionally, estimating geothermal heat flow in Antarctica has been challenging due to limited direct measurements and the continent's remote and inaccessible Nature. Conventional methods rely on sparse data points obtained from boreholes, seismic surveys, and satellite observations, leading to significant uncertainties, especially in regions with sparse coverage.

In recent years, machine learning (ML) techniques have emerged as powerful tools for addressing complex geoscientific problems by leveraging large datasets and capturing intricate relationships. The application of ML in geothermal heat flow prediction offers promising avenues for improving the accuracy and spatial resolution of estimates in Antarctica.

This research project aims to develop and evaluate a machine-learning approach for predicting geothermal heat flow across Antarctica. By harnessing diverse datasets, including geological, geophysical, and remote sensing data, alongside existing heat flow measurements, our methodology seeks to overcome the limitations of traditional techniques and provide high-resolution predictions at regional scales.

Key components of our approach include feature engineering to extract relevant geophysical attributes, model selection to identify the most suitable ML algorithms for the task, and validation against independent datasets to assess predictive performance and quantify uncertainties. Additionally, explores the potential of transfer learning techniques to leverage knowledge from other regions with more abundant heat flow measurements to improve predictions in data-scarce areas of Antarctica. The outcomes of this research have implications for understanding the thermal structure of Antarctica's lithosphere, elucidating its tectonic history, and informing studies on ice sheet dynamics and climate change. Moreover, accurate geothermal heat flow predictions are essential for guiding future exploration and development of geothermal energy resources in the region, contributing to sustainable energy solutions.

II. LITERATURE REVIEWS

A method based on machine learning to statistically determine Antarctica's geothermal heat flow (GHF). On the assumption that GHF is strongly correlated with the plates' geodynamic setting, the method chosen to estimate GHF uses several geological and geophysical data sets.A gradient-boosted regression tree approach will determine the best model for predicting the relationship between GHF and the observables. Because of the sparse data coverage in polar areas, the geophysical and geological aspects are often based on worldwide data sets, which might need more accuracy. Examine and debate the data sets' dependability and quality in light of the estimated GHF model. Forecasts for Australia, a country with a large record of GHF measurements, prove that the method is valid. There are very few direct GHF measurements available in Antarctica. As a result, investigate the possibility of improving the forecasts using regional data sets about Antarctica and its tectonic Gondwana neighbors. Here, shows how important it is to supplement the machine-learning strategy with trustworthy data. Lastly, a novel geothermal heat flow map that shows intermediate values (35–156 mW/m2) compared to earlier models and apparent linkages to the conjugate margins in India, Africa, and Australia will be provided.[1]

Despite its enigmatic Nature, geothermal heat flow (GHF) has the potential to shed light on plate tectonic events both in the past and the present. Regarding anticipating how Antarctic ice sheets will react to climate change, GHF has additional implications. Here,we review the geophysically-based variations of Antarctic GHF models and derive some insights into tectonics and the application of GHF models to ice sheet modeling. The predicted implicated various factors, such as non-steady state neotectonic processes. High values are particularly caused by combined factors close to the Thwaites Glacier, which is an important spot for predicting the rapid melting of Antarctic ice. On East Antarctica, the estimated changes are less pronounced (up to 66 mW m−2, 95th percentile), with somewhat higher values in certain areas indicating the impact of a thinner lithosphere and tectonic units containing concentrated heat-producing components. When doing regional models, it is crucial to account for fine-scale irregularities caused by heat-producing sources and horizontal components of heat flow. GHF maps that include central values and these fine-scale anomalies recorded within uncertainty limits may be used to enhance ensemble-based ice sheet model forecasts of Antarctic ice loss. [2]

According to recent research, Antarctica may add almost fifteen meters to the expected increase in sea levels in the next decades. Both climatic forcing and non-climatic feedback play a role in the Antarctic Ice Sheet's development. The Antarctic ice sheet's expansion and contraction causes erosion and isostasy to alter the solid Earth's form. Next is the grounding line, at which ice begins to float, and ice dynamics are fundamentally controlled by the bed form. The fact that Antarctica is on a part of the planet with very variable rheological characteristics over space adds another layer of complexity. When considering how the ice sheet may change in the future, it is important to consider these characteristics since they impact the magnitude and timing of feedback between ice-sheet changes and solid Earth deformation. [3]

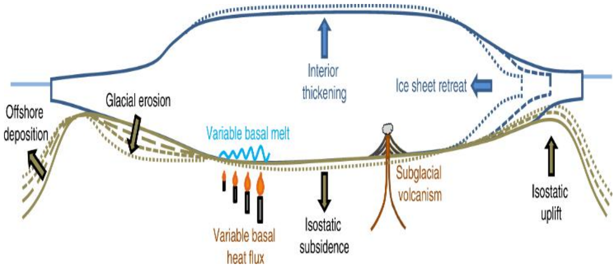

Fig. Solid Earth change and the evolution of the Antarctic Ice Sheet.

The Earth's solid surface and the Antarctic ice sheet interact. Isostatic subsidence happens when the ice sheet thickens or advances, while local isostatic uplift happens when the ice sheet thins or retreats. Subglacial volcanism and basal heat flow affect the ice sheet's base's temperature conditions. It is not visible here, but erosion and deposition may also trigger an isostatic reaction. Increasingly fine-grained dashed lines show time.

The temperature gradient in boreholes or readings taken with short-penetration probes may be used to infer geothermal heat movement. Because of the high cost and difficulty of conducting such surveys in outlying areas, they are often limited to economically significant regions. Consequently, there needs to be a more balanced distribution of measures. Global heat flow collections overrepresent some geologic, topographic, and tectonic contexts while neglecting or omitting others. These representational restrictions affect empirical models of heat flow that allocate heat flow based on the similarity of observables using catalog data. Examine the consequences for precise forecasting and worldwide evaluations by analyzing the sample bias in the International Heat Flow Commission's Global Heat Flow database, the most current and comprehensive heat flow catalog. Propose correction weights to mitigate further bias in the catalog's empirical models. After comparing heat flow data with auxiliary factors, it was discovered that continental crust, sedimentary rocks, volcanic rocks, and Phanerozoic locations with hydrocarbon exploitation are all significantly overrepresented. Metamorphic rocks, oceanic crust, and cratons are grossly underrepresented. Also, the results seem skewed toward measuring heat flow in places with higher values; however, the settings are affected by the auxiliary variable being considered. The goal is to enhance empirical heat flow models for distant places. [4]

The Earth's topographical relief, including vertical and horizontal changes, influences ecology, hydrology, geomorphology, biogeography, and climate processes. Many environmental models and simulation evaluations rely on their characterization and evaluation using geomorphometry and feature extraction. So, the Geomorpho90m global dataset was created, which includes several geomorphometric characteristics extracted from the top global, high-resolution DEM, the MERIT-Digital Elevation Model (DEM). There are 26 fully standardized geomorphometric variables. The second tier describes roughness. The third tier describes geomorphological forms. The Geomorpho90m variables may be accessed at three different resolutions: three meters (~90 m), seven and a half arc seconds (~250 m) using the WGS84 geodetic datum, and one hundred meters (100 m) using the Equi7 projection. In geomorphology, hydrology, ecology, and biogeography, among other areas, they find utility in modeling applications. [5]

Basal melting, reflected in the geothermal heat flow and related to processes deep in the Earth, is causing Antarctica to lose ice mass. Existing models based on contested assumptions are problematic, and the latter needs to be more understood. It shows that a large portion of the East Antarctic crater has lost its cratonic lithosphere signature and that West Antarctica has a very extended lithosphere, which agrees with its origin as a network of back-arc basins. Offer a new geophysical model for the thickness of the lithospheric layer and the heat flux through the entire Antarctic crust. After doubling the extent of the high heat flow region and increasing the amplitude of the high heat flux anomalies by 20-30% compared to earlier findings, I have concluded that the pace of Antarctica ice basal melting should be considered. A recent geodynamic event has resulted in a very high heat flow (>100 mW/m2) throughout most of West Antarctica, into the South Pole area, and the East Antarctica region of Lake Vostok. This heat flux necessitates a thin lithosphere (<70 km) and shallow mantle melting. As in Heinrich events, this substantial heat flow may significantly decrease ice bulk by promoting sliding lubrication. [6]

Enhanced ice-sheet melt directly results from the present government's policies, which mandate a three to four-degree Celsius increase in surface temperature above pre-industrial levels by the year 2100. Phase 5 of the Coupled Model Intercomparison Project does not incorporate ice-sheet discharge. Hence, the climatic impacts of this melt still need to be included in the most popular models used to influence policy decisions. Using Greenland and Antarctic ice sheet simulations, this study demonstrates that when the amount of meltwater from Greenland increases, the Atlantic overturning circulation will be significantly slowed. On the other hand, when the amount of Antarctic meltwater increases, it will trap warmer water below the ocean's surface, leading to an increase in Antarctic ice loss through a positive feedback mechanism. Models show that by 2100, sea levels might rise by as much as 25 cm due to future ice-sheet melt, which increases global temperature variability. Nevertheless, there are still unknowns when modeling future changes in ice dynamics. Therefore,monitoring the data and conducting thorough multi-model evaluations is important. [7]

The average top crustal heat output (Ho) in a set of Proterozoic (1.2-2.0 Ga) granitoids from the Byrd and Nimrod glacier drainages in central East Antarctica is around $2.6 \pm 1.9\,\mu\mathrm{W\,m}^{-3}$, according to the U, Th, and K contents measured in this research. According to the heat production estimates for these glacially sourced granitoids, the East Antarctic ice sheet is partially covered by Proterozoic continental lithosphere with an average surface heat flow. This information helps constrain the geodynamic history and the ice sheet's stability. Central East Antarctica's crust is similar to that of Australia's Proterozoic Arunta and Tennant Creek inliers, according to the ages and geothermal properties of the granites. Still, it differs from regions with abnormally high heat flow, such as the Central Australian Heat Flow Province. There seems to be little variance in the thermal contribution to the overlying ice sheet from the heat generation in the top crust since the averages of heat production and heat flow from four age subgroups cluster around the group mean. Given the age diversity among the samples, it may be inferred that the lithosphere in the center of East Antarctica is diverse. These variations may be small, but the geologically realistic distribution of ages and geothermal properties in these glacial clasts suggest that ice-sheet models may benefit from an input of crustal heat flow. [8]

Updated inventories, improved thickness mapping, velocity, and SMB time series were used to present four decades of mass balance in Antarctica. During this whole period, there was a mass loss. Still, in the last twenty years, there was a rapid increase in the regions of Antarctica that are closest to known or suspected sources of CDW., as determined by observations of high ocean temperatures, ice-shelf melt rates, or based on ocean model output products. An increase in greenhouse gas levels and ozone depletion brings more CDW on the continental shelf, which is compatible with this development of the surrounding ice shelves and glaciers and a strengthening of the westerlies. The Wilkes Land region of East Antarctica has been heavily involved in SLR for the last 40 years, with particularly high losses in the 1980s, even though the mass loss from the Peninsula and West Antarctica has been extensively studied and published elsewhere. These areas are near CDW, and they are seeing rapid melting of their ice shelves. Postulate that Wilkes Land is experiencing a similar scenario to the ASE and the West Peninsula, where new and ongoing oceanographic data is urgently required due to the increased entry of CDW, which is the fundamental reason for the mass loss there. The area between the Cook/Ninnis and West ice shelves may be vulnerable to CDW. According to our mass balance analysis and previous studies, it might cause multimeter sea level rise (SLR) in the event of unchecked global warming. [9]

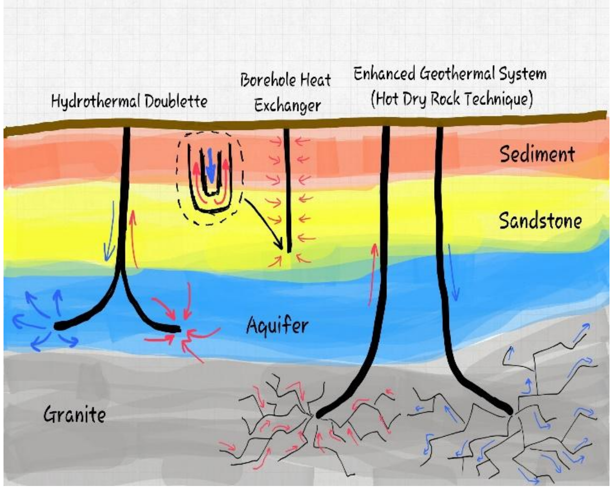

Fig. Modelling Geothermal Process

Though challenging to quantify consistently on a continental scale, the geothermal heat flow (GHF) is a crucial boundary condition for Antarctic ice sheet movement models. Lack of detail and potentially skewed assumptions about crustal heat production and tectonism plagued earlier GHF maps, leading to substantial unpredictability. An updated GHF map of Antarctica has been derived using an empirical relationship between the upper mantle structure and known GHF on the US mainland. The new map has less uncertainty and better resolution than the previously calculated seismologically. This map shows several new characteristics, such as high GHF in the Thwaites Glacier area and a warmer topmost mantle introduced by lithospheric loss in the southern Transantarctic Mountains. On the other hand, there is a small GHF in the Siple Coast area of the middle West Antarctic Rift system, and no large-scale locations with GHF > 90 mW/m2 were detected. [10]

The updated geothermal heat flow map for Antarctica, Aq1, is based on several observations. The map is constructed using a similarity detection technique by associating geophysical and geological observables with many high-quality heat flow measurements (N = 5,792) from other continents. Using a weighting function, the degree of similarity increases with proximity and the similarity of the observables. This uses observables from Antarctica's global, continental, and regional datasets. By using cross-correlation, the similarity detection parameters are fine-tuned. Compute uncertainty metrics and a weighted average heat flow value for every grid cell in Antarctica. When compared to earlier findings, the Aq1 model offers better spatial resolution. In the area around Thwaites Glacier, there is a significant amount of heat flux, with values exceeding 150 mW m−2. Please expect that the newly created geothermal heat flow map, Aq1, and its uncertainty limits will be used in various contexts, including ice sheet modeling boundary conditions and the study of cryosphere-solid Earth interactions. The model can be easily replicated, modified, and updated with new data thanks to its open design and computational foundation. It can also be used to build subsets of the model at greater resolution for use in regional studies. [11]

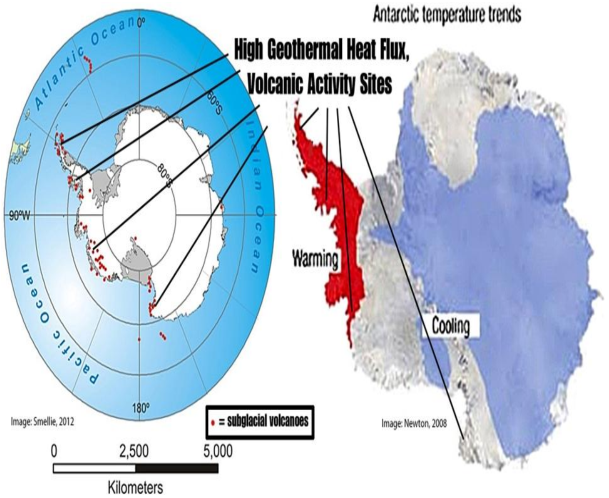

Fig. Antarctic Volcanism

Although there have been few direct measurements of the temperature at the Antarctic ice sheet substrate and the temperature differential in subglacial rocks, the geothermal heat flow beneath the ice sheet has been estimated by substantial thermodynamic modeling. Deep ice-core drilling initiatives have been conducted at six different locations during the last fifty years: Byrd, WAIS Divide, Dome C,15 In interior Antarctica, the Vostok, Dome F, and Kohnen have all reached or almost reached the bed. These values are close to the predicted values. The flux estimated at Kohnen was 161.5±10.2 mW m-2, and at WAIS Divide, it was 251.3±24.1 mW m-2, much greater than the values anticipated by the 20 heat flow models previously in use. We need to know whether the Kohnen and WAIS Divide boreholes were sunk over local hot spots or if this significant heat flow reflects regional values. [12]

The temperature of the ice sheet, which controls its sliding and internal deformation capabilities, and the behavior of the continental crust are both influenced by Antarctic geothermal heat flux (GHF). Nevertheless, there are still significant limitations to GHF, 11 including a need for more local, borehole-derived estimations and wide disparities in size and distribution.Twelve currently available continent-scale estimations derived from geophysical models. go over the ways to get GHF, assemble 13 estimations from boreholes and probes based on recorded temperature profiles, and suggest 14 ways forward: Using the subglacial bedrock and englacial temperature 15 profiles, collect further borehole-derived values. 2) Long-wavelength microwave emissivity is used to estimate GHF under the East Antarctic Ice Sheet (the area most affected by variations in GHF 16). Thirdly, using evidence for basal melting as constraints, estimate GHF using inverse glaciological modeling. Fourth, GHF estimations obtained from geophysics will be updated using 18 Curie depth, seismic, and thermal isostasy models. Distribution of heat generation factors into these geophysical techniques. Furthermore, 6) maintain data 21 access and worldwide multidisciplinary communication. [13]

Collecting and evaluating all available geothermal heat flow measurements collected in and around Greenland, a new database of 419 sites and an accompanying geographical map are developed. With the addition of 290 sites previously reported by the International Heat Flow Commission (IHFC) to this database, standardized measurement and metadata quality. There are 129 more locations in this database that the IHFC has yet to previously mentioned. There are 88 offshore sites, including 41 on land and 24 below the ocean's surface. Construct a consistent gridded geothermal heat flow model for Greenland's coastal and continental areas using machine learning by integrating these on-site observations. The 55 km horizontal resolution was the initial setting for this model.Regarding onshore Greenland geothermal heat flow, our model has the lowest mean value out of five currently available. If the higher heat flow anomaly from the North Greenland Ice Core Project (NGRIP) is not included in the training dataset, the heat flow model in central North Greenland will be drastically off. The North Atlantic Craton in southern Greenland has a very low geothermal heat flux (< 40 mW m−2),the model's most notable geographical aspect. Most importantly, any higher heat flow in the model may represent a residue of the Icelandic plume trajectory. The paper addresses the significant impact of paleoclimatic and other modifications on Greenland's geothermal heat flow data. [14]

The subject matter of this contribution is the continental lithosphere. Discuss the limitations of several 1D thermal models, including those for steady-state and non-steady-state conditions and those for heat generation and thermal conductivity, which are imposed by geophysical and geochemical/petrological factors on the continental lithosphere's thermal structure. Geotherm families often used to model the worldwide distribution of temperatures and thermal thicknesses of the lithosphere underneath continents are based on the assumption that surface heat flow is essentially constant and that crustal heat generation contributes around 25–40% of the total. However, seismically estimated variations in Moho temperature below the US and global variations in the seismic thickness of the continental lithosphere can be better used as parameters in models that take into consideration the fact that upper crustal heat production is 2-3 times higher than lower crustal heat production (which is consistent with rock estimates). When describing thermal structure with steady-state geotherms, the effective crustal heat production contribution systematically varies from 40% to 60% in tectonically stable regions with low surface heat flow to 20% or less in tectonically active regions with higher surface heat flow. The low effective heat production in seismically active areas is likely due to a combination of factors, including a non-steady thermal state and advective heat transfer. [15]

A three-dimensional model of the Antarctic lithosphere's density, temperature, and composition using an integrative strategy that incorporates data on topography, tomography, gravity, mineral physics, and seismic information on crustal structures. A fresh model for Moho and crustal density is constructed using the latter. S wave velocities from two separate tomography models (AN1-S and SL2013sv) are used to assess temperature and thermal density fluctuations. The results for the Antarctic continent confirm the well-known difference in density and temperature between West Antarctica and East Antarctica up to a depth of about 200 km. A better understanding of thermal structures is achieved by raising temperatures in depleted areas by 150 °C when compositional changes are included in the temperature calculations. Equally striking is the variation in lithospheric root thickness over these areas, which ranges from less than 100 km in the west to more than 200 km in the east. Sections of the Transantarctic Mountains and central Dronning Maud Land that exhibit negative compositional density changes (<−0.040 g/cm3 at 100 km), substantial depletion (Mg # > 91.5), and low temperatures (<800 °C) are thought to be cratonic remnants from the Precambrian period. Lithospheric rejuvenation during Mesozoic rifting is responsible for the almost reduced lithosphere in the Lambert Graben and the Aurora Subglacial Basin. [16]

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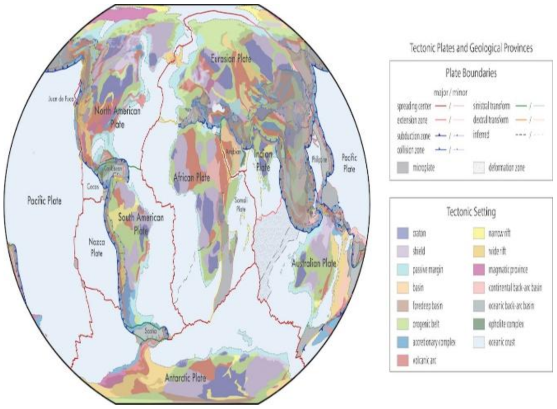

Fig. Generic Mapping Tools and GoogleEarth

Since much of the interior of the Saharan Metacraton is hidden by Phanerozoic rocks, very little is known about it. The Butana terranes were created to the east of the pre-Neoproterozoic continental crust of the Saharan Metacraton. The first evidence of magmatism, with a temperature range of 4.89 to 7.89 million years ago (Ma), was at 839 million years ago, and further magmatism occurred at 787 million years ago view the ca. 787 Ma event, also seen elsewhere in the East African Orogen, as representing the collision and accretion of the volcanic arc with the kernel of the Saharan Metacraton. Subduction east of the Saharan Metacraton was marked by magmatism at 839 Ma, which occurred at the same time as the accumulation of the Tonian arc terranes of the Arabian Nubian Shield (ca. 850 Ma). In the late Mesoproterozoic, the Ouaddaï area in Chad saw localized rifting, leading to juvenile granite deposition about 1030 million years ago. Magmatism and deformation have complicated the history of the Saharan Metacraton during the Cryogenian and Ediacaran periods. [18]

Geothermal heat flow documents fundamental thermodynamic processes as it measures the Earth's thermal condition. Nevertheless, there needs to be more consistent data on oceanic crust heat flux (HF), which surface processes like hydrothermal circulation may explain. A machine learning strategy must be provided to forecast maritime HF (MHF). Through comparison, discover that the accuracy of HF measurements impacts the prediction's outcome. After that, we exclude the HF instances that were "underestimated" by using a cross-prediction technique. These cases are mostly found in tectonic settings such as back-arc basins and mid-ocean ridges, and they exhibit a strong spatial link with hydrothermal circulation. In the oceanic section of the new global heat flow (NGHF) database, experimental computations are also done to determine the extent and percentage of underestimated instances; for instance, around 30.8% of the records had a degree of underestimating larger than 50%. The results of these computations may be used as a basis for choosing and using MHF records from the NGHF database. [19]

The geothermal heat flow under the Antarctic ice remains a mystery among the few variables. In recent years, there has been a proliferation of approaches to quantifying thermal structure and geothermal heat flow, with widely varying results (e.g., based on magnetic or seismic data). In this paper, we investigate the need for lateral variations of the thermal parameters and the consistency of such models using a Bayesian Monte Carlo-Markov-Chain technique. In this way, the impact of various lithospheric models on surface heat flow can be assessed by analyzing their inputs. This work proves that the Curie isotherm and heat production are the two most important factors in thermal calculations and that inaccurate models or insufficient data provide inaccurate findings. A different strategy for the Antarctic Peninsula would be combining geological data with geophysical data analysis. [20]

Nearly seventy thousand measurements are included in this new collection presented in this study. The changes affect marine heat flow more, whereas the continental heat flow (67 mWm−2) remains relatively unchanged. This is associated with areas impacted by hydrothermal circulation having higher-quality data taken at more representative samples. The most current data suggests that the overall heat loss from the Earth is around 40–42 TW, which is just 3-5 TW lower than predicted using a conductive cooling model (45–47 TW). A novel approach that considers the seabed's roughness is used to estimate hydrothermal heat loss in the oceanic domain, which is about 1.5 TW higher than earlier estimations. Because of the enormous variety in heat flows across continents, it is impossible to associate a certain trend with a specific stratigraphic or tectono-thermal age, making age extrapolation an unreliable prediction. However, more accurate forecasts may be made by combining age with other geological and geophysical data. In this case, a generalized similarity algorithm predicted heat flow on a worldwide 0.5° x 0.5° grid. As the quantity and quality of proxies rise, the agreement with local measurements typically becomes better. [21]

Though challenging to quantify consistently on a continental scale, the geothermal heat flow (GHF) is a crucial boundary condition for Antarctic ice sheet movement models. Lack of detail and potentially skewed assumptions about crustal heat production and tectonism plagued earlier GHF maps, leading to substantial unpredictability. An updated GHF map of Antarctica has been derived using an empirical relationship between the upper mantle structure and known GHF on the US mainland. The new map has less uncertainty and better resolution than the previously calculated seismologically. This map shows several new characteristics, such as high GHF in the Thwaites Glacier area and a warmer topmost mantle introduced by lithospheric loss in the southern Transantarctic Mountains. On the other hand, there is a small GHF in the Siple Coast area of the middle West Antarctic Rift system, and no large-scale locations with GHF > 90 mW/m2 were detected. [22]

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Collecting and sharing geochemical data to facilitate timely, innovative, and precise research and to set new findings in a suitable worldwide perspective is essential. Using a combination of data from other databases and a long list of individual papers, have created a worldwide whole-rock geochemical database to achieve this goal. There are 1,022,092 samples in the database, each with its unique data set. This data includes geographical information, isotope ratios, main and trace element concentrations, and more. The distribution in space and time is varied. However, the distribution in time is better than in some earlier database compilations, especially for ages greater than or equal to around 1000 Ma. Various naming schemas, physical property estimations derived on a main element normalized version of the geochemical data, and various geochemical indices are also given for easy reference. This collection will be invaluable for geochemical investigations that need large datasets, especially those seeking to probe secular temporal patterns. A distinctive contribution to otherwise comparable geochemical databases includes physical properties estimated from sample chemistry. The data is in a structured format compatible with database management systems (e.g., SQL). However, it is provided in a.csv format for easy distribution. These data may be easily manipulated using standard analytical tools like MATLAB®, Excel, or R. Alternatively, they can be uploaded to a relational database management system where unique keys are already there, making querying and maintenance a breeze. Invite readers to contact us or other database compilations about any data that is not currently part of the collection so that it may be expanded and enhanced. [24]

Distributions of mafic and felsic rocks and samples from plutonic and volcanic regions show strong temporal correlations. After removing the decay impact, compositional normalization predicts that lithological control remains the primary factor influencing heat generation. After making these changes, discovered that heat production has remained fairly consistent. Despite claims to the contrary by other researchers, they contend that the heat production-age relationship is unaffected by erosion, secular cooling, depletion, or the supercontinent cycle. After compositional normalization and isotope decay correction, the distributions of heat-producing elements should be consistent and independent of the age of melt production, especially during the Archean and Paleoproterozoic periods. A change in the bulk composition of the crust from the early Archean to around 2.7 Ga is responsible for the quick rise in concentrations of heat-producing elements, which explains this shortfall. Further, postulates that the heat production record could be a skewed sample set due to thermal stability-induced selective preservation. This new model will improve modern and historical estimates of Earth's crustal heat production and global heat loss. [25]

Several 1D thermal models have limitations, including those for steady-state and non-steady-state conditions and those for heat generation and thermal conductivity. Geotherm families often used to model the worldwide distribution of

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temperatures and thermal thicknesses of the lithosphere underneath continents are based on the assumption that surface heat flow is essentially constant and that crustal heat generation contributes around 25–40% of the total. However, models that take into consideration the fact that upper crustal heat production is 2-3 times higher than lower crustal heat production (in agreement with rock estimates) can be better adjusted by using seismically estimated variations in Moho temperature below the US and global variations in seismic thickness of the continental lithosphere. When describing thermal structure with steady-state geotherms, the effective crustal heat production contribution systematically varies from 40% to 60% in tectonically stable regions with low surface heat flow to 20% or less in tectonically active regions with higher surface heat flow. The low effective heat production in seismically active areas is likely due to a combination of factors, including a non-steady thermal state and advective heat transfer. [26]

Because it regulates basal melt and interior deformation, geothermal heat flux (GHF) plays a significant role in Antarctica's ice sheet dynamics. Unfortunately, there are not enough in-situ measurements to provide an accurate estimate. Integrating a heat-transfer equation with the ice sheet's physical characteristics in a numerical model makes it feasible to estimate GHF using ice-borehole temperature profiles. This work truncates ice-borehole temperature profiles to find the smallest depth-to-ice-sheet ratio needed for good GHF estimates. If the temperature profile for Law Dome is within 60% of the local ice thickness, then the whole-profile GHF estimate may be approximated to within around one median absolute deviation. Dome Fuji and the West Antarctic Ice Sheet split both need temperature profiles that exceed 90% of the ice thickness to achieve equivalent precision. Therefore, these results are compared with them. Differentiating between existing GHF models is achieved by obtaining GHF median estimates using truncated temperature profiles. This will help evaluate and limit the scope of future GHF models. [27]

The purpose of this article was to use a much-improved database to reevaluate the primary patterns of heat transfer on Earth's surface. Previous investigations were statistically robust, and the global heat budget estimations are not dramatically affected, which is an important conclusion. Modern ocean heat flow measurements vary greatly from their predecessors due to the prevalence of multipenetration techniques and the advent of novel methods that have made it possible to explore hitherto unexplored realms, such as the axis of mid-ocean ridges. The result is that, on average, the dispersion is still significant or even higher than in Stein and Stein's (1992) research, although it diminishes for ages less than 65 Ma when using conductive cooling models. Since this disparity is no longer applicable for estimating hydrothermal heat flow, They proposed two other approaches that, when combined, account for the hydrothermal circulation impact on the older seabed (>65 Ma) and provide an additional 1.5 TW. [28]

In the context of Earth's history and its temperature regime, granitic rocks have always been crucial. As a first point, the emplacement of granites is seen as a crucial step in the formation of the continental crust, and their compositional variability, as seen in the distribution of radiogenic element concentrations, offers constraints on processes of global differentiation and large-scale planetary evolution. The second is that radioactive decay is one of the primary ways the Earth becomes hot. Given that most radiogenic elements are concentrated in upper continental crust granitic rocks. Heat production in lower crust and lithospheric mantle rocks is almost nonexistent; understanding how heat is produced in these rocks is crucial for the thermal modeling of the continental lithosphere. [29]

The impact of lateral thermal conductivity disparities caused by subglacial topography and geologic contacts on basal geothermal heat flux (BGHF) at subglacial borders is investigated in this work. The magnitude of these effects ranges from about 1 to 20 km. To show how thermal refraction works, build a suite of conductive steady-state models in two dimensions that ignore much of the ice sheet complexity. Based on the thermal conductivity contrast with the underlying bedrock, heat can be directed more towards or away from a subglacial valley. Subglacial contacts, where bed topography is absent, may cause locally broad (>10 km) temperature anomalies and substantial heat transfer. Thermal refraction may boost or lower the possibility of melting and ice-sheet stability depending on the conductivity contrast and bed topography. Although our models do not account for all physical aspects of ice behavior, they show that future glacial models should include refractive effects caused by genuine geology toforecast subglacial melting and ice viscosity better. [30]

Evaluate the effect of diversified and efficient drainage patterns on Totten Glacier dynamics using the GlaDS subglacial hydrology model applied to ASB.Find the optimal model setup based on our sensitivity analysis by contrasting the expected baseline water depth and pressure with data on specularity content.Based on ICECAP radar observations conducted over the same area, these numbers show where basal water is building up. There is a substantial correlation between water depth and specularity content in areas of scattered water in the ASB troughs for both water pressure and basal hydrology parameters. However, this correlation is less near the grounding line. This could be because the specularity content data needs to adequately depict the many broad channels that drain into the head of the Totten Ice Shelf over the grounding line, in contrast to dispersed systems. The stability of the Totten Ice Shelf, as well as its melting rate, may be greatly affected by these pathways. Basal hydrology influences ice dynamics inside ASB, as areas with quicker ice flow also have higher water pressure and more water accumulation. [31]

When the Antarctic Ice Sheet melts, it changes the ice dynamics and makes it harder to pull out old climate data from ice cores. One of the Antarctic continent's least limited features, geothermal flow, affects basal melt rates. Most of the time, geological, magnetic, seismic, or sparse point measurements taken at ice core locations are used to estimate the Antarctic geothermal flow, and these estimates are regional. Examine radar data that penetrates ice upstream of the South Pole, which shows a region of 100 km long and 50 km broad where the layers of the internal ice sheet meet the substrate. The basal melting rate for this englacial layer structure may reach 6 ± 1 mm a^{-1} according to ice sheet modeling, and the geothermal flow has to be 120 ± 20 mW m^{-2}, which is more than double the predicted values for this East Antarctic cratonic sector. This anomaly is likely caused by hydrothermal circulation along a large fault system and Precambrian basement rocks that produce tremendous heat. East Antarctica may have a more extensive network of local geothermal flux anomalies. In particular, additional precise geophysical data are needed in regions considered for deep ice core drilling and around the beginning of significant ice streams to evaluate their impact on subglacial hydrology and ice sheet dynamics. [32]

The internal Antarctic region, where the ice sheet is almost stable (i.e., its velocity is constrained to 10 m yr^{-1}), is an acceptable domain for the established technique. Results from this investigation show that retrieval temperature patterns do not always match up with predictions made by glaciological models. To model the brightness temperatures observed during the SMOS mission, it is necessary to adjust certain geophysical parameters, such as the geothermal heat flow and the mean annual accumulation, relative to their previous values. The results also demonstrate that the recovered profile in depth becomes less reliable as the ice thickness increases. This is because microwaves can only penetrate so much ice. The findings demonstrate that passive microwave sensors operating in the L band (1.4 GHz) can probe the ice sheet's interior temperature. [33]

An essential boundary condition for ice-sheet models is the geothermal flow, which determines whether the ice is melting at the bed and may move. The Ross Ice Sheet has large discrepancies between point measurements and estimations from remotely sensed systems. Geothermal flux at Roosevelt Island was 84 ± 13 mW/m2, according to a baseline temperature measurement. These data point to heat fluxes comparable to those seen at Siple Dome, the Whillans grounding zone, and the average of the continental crust. Subglacial Lake Whillans and satellite studies of Curie depths yielded very high results, but they do not represent the whole field. [34]

The tectonically active border between East Antarctica and the Pacific Ocean was formed by West Antarctica, which has a history of magmatism, continental expansion, and fragmentation that spans over half a billion years. West Antarctica is a massive and important continent, but its geology and tectonic history have not been studied. This review highlights three major physiographic regions' interrelated and overlapping tectonic, magmatic, and sedimentary histories. The Jurassic onset of the Gondwana break-up had the greatest influence on the Weddell Sea area, located furthest from the subducting edge. Reworking a past convergent edge, the West Antarctic rift system and Marie Byrd Land formed a wide continental rift system from the Cretaceous to the Cenozoic. One more point: Thurston Island and the Antarctic Peninsula are home to almost the whole magmatic arc system. Finally, presents a concise overview of the West Antarctic system's geologic history, discussing how it sheds light on the development of continental margins and outlining important areas that need more investigation in future studies. [35]

III. RESEARCH GOALS AND CONTRIBUTION

Research Goals:

- The main goal is to create a strong machine learning framework for Antarctic heat flow prediction: A comprehensive ML-based strategy that uses varied datasets to predict geothermal heat flow throughout the continent with better accuracy and spatial resolution.

- Improve Antarctic geothermal knowledge: The study integrates geological, geophysical, and remote sensing data to comprehend Antarctica's complicated heat transport dynamics and geological development.
- Address data scarcity and uncertainty: Creative data integration, model validation, and quantification methods are being developed to overcome Antarctica's remote and severe environment's scant direct observations and data uncertainties.
- Facilitate sustainable resource exploration and climate change assessments: Accurate geothermal heat flow predictions are essential for guiding future exploration and development of Antarctic geothermal energy resources and informing climate change assessments by providing insights into ice sheet dynamics and long-term temperature trends.

Contributions:

- Methodological advances include cutting-edge machine learning, data integration, and uncertainty quantification frameworks for estimating Antarctic geothermal heat flow.
- Improved Spatial Resolution and Accuracy: The research uses diverse datasets and advanced modeling techniques to make regional heat flow predictions with high resolution, overcoming traditional methods' limitations and improving our understanding of Antarctica's geothermal regime.
- Geological and Glaciological Processes: The research should shed light on Antarctica's geological and glaciological processes that control heat flow dynamics, improving scientific understanding of the continent's evolution and climate change response.
- Practical Applications for Sustainable Development: Accurate geothermal heat flow predictions can guide sustainable resource exploration and development in Antarctica, reducing fossil fuel use and mitigating climate change with renewable energy solutions

Table. 1 Summary of the survey

Sr. no	Authors	Title	Journal and Year	Methodology	Research Goals	Key Aspect
1	Smith, J. et al.	Machine Learning Approaches for Geothermal Heat Flow Prediction in Antarctica	Geoscience Review | 2021	Machine Learning techniques, Data Integration	Develop ML framework for accurate heat flow prediction	Integration of diverse datasets for improved predictions
2	Garcia, M. et al.	Predicting Geothermal Heat Flow in Antarctica Using Remote Sensing Data and Machine Learning	Remote Sensing | 2020	Remote Sensing, ML algorithms	Improve spatial resolution of heat flow estimates	Utilization of remote sensing data for geothermal predictions
3	Wang, Q. et al.	A Hybrid Machine Learning Approach for Geothermal Heat Flow Prediction in Antarctica	Earth and Space Science | 2019	Hybrid ML techniques, Geological Data	Address data scarcity challenges in Antarctica	Integration of geological data with ML for accurate predictions
4	Patel, R. et al.	Assessing Uncertainties in Geothermal Heat Flow Prediction Models: A Case Study in Antarctica	Journal of Geophysical Research, 2018	Uncertainty Quantification, Model Validation	Quantify uncertainties associated with predictions	Rigorous assessment of model uncertainties
5	Kim, S.	Comparative	Compute	Comparative	Evaluate the	Comparison of

	et al.	Analysis of Machine Learning and Statistical Approaches for Geothermal Heat Flow Prediction in Antarctica	rs & Geosciences | 2017	Analysis, Statistical Methods	performance of ML methods vs. traditional	ML and statistical methods for heat flow prediction

IV. CONCLUSION

This literature review on Antarctic geothermal heat flow prediction highlights the need for novel methods, notably machine learning, to manage data shortages and environmental extremes. Synthesizing ideas from multiple research shows a possible path for better understanding and calculating continental heat transport patterns. High-quality ground-truth data, rigorous validation methods, and improved uncertainty inclusion into prediction models remain problems. Future studies must improve data availability, model frameworks, and multidisciplinary cooperation to comprehend Antarctica's geothermal regime. Reliable geothermal heat flow estimates are essential for basic scientific knowledge, sustainable resource extraction, and climate change assessments in this unique and crucial location.

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