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COMMENTARY
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Special Section:
The Power of Many: Opportunities and Challenges of Integrated, Coordinated, Open, and Networked (ICON) Science to Advance Geosciences

Key Points:

- Data accessibility is not consistent across Geomagnetism, Paleomagnetism, and Electromagnetism (GPE) disciplines. Some have a long tradition; others are still developing capabilities
- A global survey of GPE labs shows that leaders are predominantly white males. A network of Science Equality Commissions may increase equality
- Earth and planetary magnetism researchers can increase global stakeholder involvement through Coordinated, Open, and Networked investment

Supporting Information:

Supporting Information may be found in the online version of this article.

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Geomagnetism, Paleomagnetism and Electromagnetism Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science

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Abstract This article is composed of three independent commentaries about the state of Integrated, Coordinated, Open, Networked (ICON) principles (Goldman et al., 2021, https://doi.org/10.1002/essoar.10508554.1) in the Geomagnetism, Paleomagnetism, and Electromagnetism (GPE) section and discussion on the opportunities and challenges of adopting them. Each commentary focuses on a different topic: Global collaboration, reproducibility, data sharing and infrastructure; Inclusive equitable, and accessible science: Involvement, challenges, and support of early career, BIPOC, women, LGBTQIA+, and/or disabled researchers; Community engagement, citizen science, education, and stakeholder involvement. Data sharing practices and open repository use still varies strongly between GPE communities. Some have a long tradition of data sharing; others are only starting it. Globally, GPE leadership is strongly dominated by white males and diversity may increase through the creation of Science Equality Commissions. Improved global stakeholder involvement can increase research impacts and help fight inequalities. In all investigated topics we see promising beginnings but also recognize obstacles that include a lack of funding, a lack of understanding of diversity, and prioritizing short-term gain over long-term benefit. Nonetheless, we are hopeful that our community will embrace ICON science.

1. Introduction

Integrated, Coordinated, Open, Networked (ICON) science aims to enhance synthesis, increase resource efficiency, and create transferable knowledge (Goldman et al., 2021). This article belongs to a collection of commentaries spanning geoscience on the state and future of ICON science.

2. Global Collaboration, Reproducibility, Data Sharing and Infrastructure

Fair access to meaningful and well-documented data is the foundation of implementing ICON-FAIR (FAIR = Findable, Accessible, Interoperable, Reusable, Wilkinson et al., 2016) principles in GPE science. Data sharing comprises the "C" for the necessary **c**oordinated effort, "O" for **o**penly available data and processing tools and "N" for the **n**etworked effort to contribute data to a wider community for mutual benefit. It further allows for **i**ntegration across disciplines ("I"), for example, between geophysics and space physics. Here we compare data sharing practices in GPE subdisciplines, identify causes of the status quo, and pathways toward equitable data access. These may also apply to model and software sharing.

The three GPE communities include **G**eomagnetism (studying Earth's recent magnetic field variations), **P**aleomagnetism (studying the Earth's past field recorded in rocks) and **E**lectromagnetism (EM) (imaging the subsurface with electromagnetic field variations). Geomagnetism has a long data sharing tradition and established

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practice. Magnetic time series from the global observatory network and derived data products are both collected by many ("N") and are openly accessible ("O"), for example, through INTERMAGNET under a Creative Commons license alongside technical documentation, software and measurement specifications ("C"). Paleomagnetism operates infrastructure for sharing measurements, meta-data, and derived products (e.g., the MagIC database (Tauxe et al., 2016). Furthermore, while MagIC captures all general aspects of paleomagnetic data, other specialized databases exist (e.g., Paleomagnetism.org (Koymans et al., 2016; 2020)) tailored to specific communities. Still, the majority of paleomagnetic data are not available in databases and only statistical descriptions of interpretations exist. This demonstrates that infrastructure is essential, but does not guarantee sharing of re-interpretable results. Data sharing in EM is even more underdeveloped, lacking generalized and agreed-upon data standards and procedures ("C" and "N"). The IRIS repository for magnetotelluric time series and transfer functions that emerged from the USArray initiative is a pioneering data repository ("O") but only holds a fraction of surveys conducted globally with a strong focus on datasets in the United States and Canada. Most electromagnetic datasets are scattered around individual websites or hosted in national data repositories.

Why have these different practices around data sharing evolved? Many aspects of modern research in geo- and paleomagnetism cannot be conducted using data from individual research groups alone, they need to be integrated ("I"). Magnetic observatories are costly to run and mostly state-funded to provide continuity. Research on the Earth's magnetic field requires global data coverage. Thus a data sharing culture is essential to these two communities due the nature of their scientific problems. In addition, geo- and paleomagnetic datasets can often be reused in different ways without necessarily generating conflicting interpretations. For example, a magnetostratigraphic study conducted to date a sedimentary section may also provide a paleomagnetic pole for plate tectonic reconstruction ("I"). EM imaging studies, however, are typically funded to perform a local to regional scale survey by a small group of investigators. The researchers involved then create a subsurface model with a satisfying interpretation. Until recently, there have been no obvious higher-order applications for such local EM datasets and making EM data publicly available has only served to establish reproducibility of results as a basis for scientific scrutiny. With the advent of research into the ground effects of Space Weather events and continental scale surveys in the past 10 years, however, legacy EM data have become interesting for a wider scientific community and have inspired new applications that were not a priority when data was originally collected (e.g., Kelbert et al., 2019). Unfortunately, the absence of data sharing standards ("C") stands in the way of developing novel data integrations and EM applications although efforts resolve this are currently under way (Kelbert, 2020). A sustainable practice that aims to implement the ICON principles should therefore be a priority of the scientific community.

Another clear benefit of data sharing is that through the preparation of data for archiving, they will be subjected to careful scrutiny, which in turn can lead to more robust interpretations. In the hectic day-to-day of scientific research, data scrutiny and diligence are often of lower priority under the pressure of finishing a manuscript for publication. Sharing data can therefore reduce the likelihood of later revisions of published work if as much importance is paid to the data product as to the interpretation. In addition, papers with associated data (or software or digital models) will generate more citations when these data are re-used. But apart from benefits toward higher-level interpretations, there is no reason in the digital era to not share data. Dedicated data publications and DOIs for submissions to repositories can amplify the rewards for the creators of such data and help offset the additional effort. In addition, open data sharing will make science more equitable and fair.

While there are still technical obstacles to making data accessible for some datatypes of our community, for example, data format issues, providing reliable meta-data, consistent data storage and access, these problems have been solved for others. The main obstacle to data sharing is cultural and financial rather than technical, and can be overcome through dialogue within the relevant communities. In this context, the mandate of AGU journals to deposit datasets used in published papers is starting to have a visible effect. After development, the support of the new practice is a cultural change, which should come from an ethical as well as scientific motive, enforced by funding agencies, publishers, reviewers, peers and editors. Many scientists have come to realize that adherence to the ICON principles is not a burden, but makes our work more relevant, more robust and more visible. We are convinced that apart from the benefit to the community, adhering to ICON principles will have a significant, positive impact on the careers of scientists that are willing to share data, and software, and facilitate innovation and integration of our fields.

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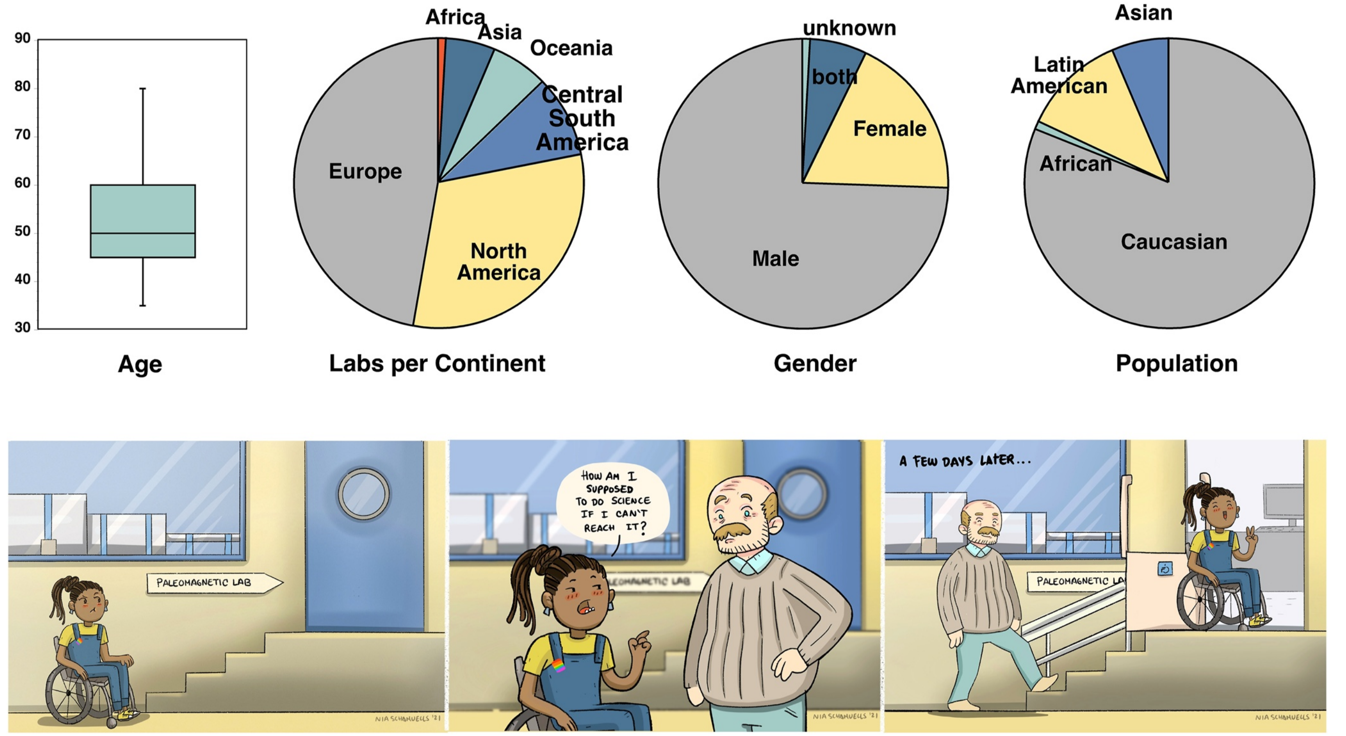

Figure 1. Top: Simplified analysis of leadership in paleomagnetic laboratories. Bottom: Toward equal opportunities in paleomagnetic laboratories.

3. Inclusive, Equitable, and Accessible Science: Involvement, Challenges, and Support of Early Career, BIPOC, Women, LGBTQIA+, And/Or Disabled Researchers

We have focused our contribution on the paleomagnetic community, starting from the information of the AGU website (https://connect.agu.org/gpe/research/labs).We fully reviewed and updated the list of groups and we performed a simple analysis by identifying the leader of each group, adding information on their age (±5 years), gender (just male/female) and known population type and disabilities. The studied sample comprises more than 100 paleomagnetic laboratories (92 originally at the AGU website): 34 in North America, 10 in Central and South America, 1 in Africa, 6 in Oceania, 7 in Asia and 53 in Europe (see Table S1). Despite the limitations (e.g., some of the websites are not updated), this preliminary analysis may show a kind of snapshot, likely unfocused, of the current situation. Ideally, a complete survey should be designed, distributed and fulfilled by all laboratories in the near future.

In any case, the image shows that about 75% of these groups are led by men, 19% by women and 6% are co-led by both genders (Figure 1, Top). It is noteworthy that the mean age of the leaders is above 50 years disclosing the difficulty of having leadership opportunities for researchers before their 40s even though they may have brilliant CVs (but not a permanent position). Another highlight is that caucasians dominate the leadership of paleomagnetic groups. More than 85% of the laboratories are located in western countries where diversity, equity and inclusion (DEI) policies are being implemented, revealing these policies need either more time to see their effects or should be revised.

No significant information is available about LGBTQIA+ or disabled groups. A thorough analysis should be done in the future to obtain a precise picture of the situation. However, we may conclude that, despite the DEI policies being implemented in universities and research centers in most countries worldwide, the average profile of a paleomagnetic laboratory leader is a caucasian mature man. Such policies are urgently needed at all levels since it will take time to see improvements.

Although in most countries there are no legal obstacles for women, BIPOC, LGBTQIA+, and/or disabled researchers to reach leadership positions, the reality is that their access may be difficult due to social (e.g., prejudices, biases in evaluations) and economical obstacles that weight down their career. What can be done? It seems necessary to promote the creation of Science Equality Commissions for each Faculty, University and Research Center, if they do not exist, and improve networking to multiply their impact. These Commissions could mentor and safeguard the rights of underrepresented researchers and prevent discrimination, and also help identify and design common research efforts and opportunities to increase equity.

4. Community Engagement, Citizen Science, Education, and Stakeholder Involvement

When considering how the GPE Section integrates ICON-FAIR principles through community engagement, citizen science, education, and stakeholder involvement, it is important to define those involved. We define the terms "community," "citizen," and "stakeholder" collectively as a people worldwide, who are not academic geoscientists but who are either interested or affected by our scientific enterprise. Understanding that opportunity gaps exist for certain communities (e.g., for "majority world" populations, BIPOC, women, LGBTQIA+ people, and individuals with disabilities), we emphasize that GPE engagement initiatives should focus on these groups of stakeholders. In every case, we must put ourselves in their shoes and ask, "what does Earth's magnetism have to do with me?"

While GPE research sheds light on topics such as the origins and current state of planetary magnetic fields, Earth's geodynamics, planetary habitability, environmental magnetism, geohealth, resource mapping, and hazard assessment, humans' general inability to perceive magnetic fields may contribute to a lack of awareness or interest from non-scientists. Observing a magnetic compass is the only tangible interaction most people have with Earth's magnetic field. There are creative ways to engage with people on magnetism and its relevance to daily life, but an organized effort is lacking. Below we highlight several examples of current successes, challenges, opportunities in paleomagnetism, and a call to action for GPE members. We regret lacking the expertise and space for discussion on the vast possibilities for stakeholder involvement in GPE topics such as environmental magnetism and look forward to future developments (e.g., Letalef et al., 2021).

One example of a high-impact outreach project is "Magnetic to the Core", an exhibit created by researchers from the University of Liverpool at the 2019 Royal Society Summer Science Exhibition (van der Boon et al., 2022). Led by Dr. Annique van der Boon, the exhibit included a three-dimensional globe that could demonstrate magnetic reversals, a field drilling station and associated picture booth, a functioning magnetometer for measuring the polarity of lava samples, and a whimsical "Rock or Choc" station, where participants used magnetic susceptibility (i.e., a compass' response) to determine whether their specimen was a real rock or a rock-like piece of chocolate. The team's utilization of everyday and custom-built instruments to demonstrate concepts of magnetism translated into successful engagements with the diverse participants (economic, age, educational background). The team published details of their exhibit (van der Boon et al., 2022), sharing insights on planning, seeking funding, budgeting, implementation (activity details) and evaluation. Publishing this information is a great example of **O**pen and FAIR principles, which GPE should strive for.

While the Royal Society Exhibition is a wonderful example of community engagement, the event is unique in its setting and funding. Geomagnetism, Paleomagnetism, and Electromagnetism members and colleagues have trouble graduating from isolated, small-dollar, one-off education and outreach projects to globally connected initiatives. Global initiatives require structured investment (time and money, e.g., dedicated outreach personnel) from professional organizations that are currently non-existent. Furthermore, without sustained commitments, there is no extrinsic motivation for workers to publish their outreach information (e.g., techniques, evaluations, and results), nor is there an ongoing forum for discussion. Therefore, we consider that GPE and similar groups would benefit from more visible investment to sustain community engagement efforts regarding planetary magnetism, mainly regarding **C**oordination of practices, **O**pen exchange of content, and **N**etworked efforts. This may include:

1. Upgrading the Teaching Resources page on the GPE website (https://connect.agu.org/gpe/) to a curated/monitored, dynamic forum capable of advertisement, growth, and analytics (perhaps in coordination with https://nagt.org/). In this "idea engine," individuals could upload/download information to tailor projects to specific audiences based on unique budgets, situations, expertise, and cultural context. Sponsoring technical sessions on outreach, education, and citizen science in GPE at large annual or semi-annual scientific meetings (e.g., AGU, EGU, GSA, Nordic Workshop, etc.);
2. Sponsoring research that gathers information from stakeholders

3. Sponsoring citizen science opportunities that intimately include non-GPE individuals in the entire process of science, while considering the individuals' motivations and skills; and most importantly,
4. Ensuring that these ideas are permanent discussion topics with consistent funding.

At first glance, community involvement in Earth magnetism research may seem difficult due to its highly technical nature; however, there are tangible examples of success that clearly demonstrate the potential for **N**etworked science opportunities. Shelby A. Jones, an archaeomagnetist and outreach educator, relied on volunteers and emerging adult interns (age 16–22) to recover 51,000 specimens of directional demagnetization data from heated archeological features (Jones et al., 2021). These data represent the foundation of archeomagnetic dating in the western hemisphere and have never before been published as an unabridged compilation. Importantly, the data are often from sites that are no longer accessible due to construction, destruction, or land usage changes. We consider Jones's project a great example of a FAIR and **O**pen exchange of data. The decades-long project consisted of developing a digital archive (e.g., scanning, digitization) and the ongoing reorganization of physical components of the scientific estates. Volunteers and interns were/are assigned diverse tasks based on their motivations and skillset, allowing them to feel valued and proud, while opening up opportunities for discovery-based research.

Projects like Jones' can serve as unique ways to include stakeholders in the process of science, while benefiting the GPE community through the progression of typically laborious tasks. Moreover, these types of projects can build trust between the public and the scientific community. The U.S. National Academies of Sciences, Engineering, and Medicine (2015) defined these types of integrated discovery-based research projects as a priority, since they improve educational outcomes in emerging adults. But the current lack of funding makes citizen science partnerships incredibly challenging. A conscious institutional investment, at both the international and local levels, is critical.

As a final note, we highlight the need for improved stakeholder involvement in paleo- and archeomagnetic sampling, which have damaged sacred indigenous and historical sites through their destructive nature. We advocate for adopting a set of best practices in sampling (Williams et al., 2021) as well as those that establish more equitable and positive interactions between researchers and communities (Butler, 2015; Mansur et al., 2017). This practice would be in the spirit of the Networked part of ICON because it involves persons beyond the immediate research team in a mutually beneficial way for everyone.

Data Availability Statement

Data were not used, nor created for this research.

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