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INTRODUCTION

The earth sciences, all sciences, are doing more and more of their activities online. Although moving online was previously a well-established trend, the COVID-19 crisis has accelerated this, as faculty, teachers, and students came to understand all too well during 2020. Ordinary activities, such as field trips, field camps, and even professional meetings like GSA 2020 Connects Online, have moved mostly online (Tikoff et al., 2020). We have had to devise new ways of teaching that are entirely outside of our experience. Rather than wistfully wishing for a return to times past, the current situation is an opportunity to explore change and depart from our old ways of doing things, striving to make our science and our geology richer to each other. Returning to and reliving the past is what we do in our geology, but it should not be what we do as geologists and scientists.

At the same time, it is becoming more critical for earth scientists, and all scientists, to better engage the public and stakeholders in their work, their data, and their insights and conclusions. We have been facing not only a pandemic of disease but also a pandemic of climate change accompanied by the malady of denying science. Because the subject of geology is our shared planet and environment, geoscientists can present much of their work in a way that is relevant to the public. We have an advantage in that the public can see what we do, look directly at what we study, and appreciate where samples come from for our analyses. The basis of our science surrounds us. The online world further opens our science, whether in geologic maps, pictures of thin sections of rocks, or a numerical age for a sample, to general observation. This new openness and connectedness can give us the power of remote participation and access.

WHAT IS DRIVING THIS?

Besides the current pandemic, what are the forces driving this change? One easy answer is that we can connect more easily to each other and resources. Connectivity is critical and foundational. It is a revolution we have been living for a long time.

Mobile devices connected to the Internet give the user access to data and information almost anywhere and anytime. You can look up references in the field or the lab. You can ask questions and instantly get answers and sometimes expert advice. In most cases, you can use cloud resources and computing power. We all know that access to language translation is available almost anywhere, not because we have a translator or program installed on our devices, but because we employ cloud and server resources by passing small amounts of information. The heavy lifting of translation is done on the other end and then communicated back to us in a compact and useful form.

However, not only do we have more and more advanced connectivity, but we all carry with us computers, in something weighing just a few ounces, that have vastly more power than was contained in desktops and computing centers just 30 years ago. Not only are mobile devices such as phones and tablets powerful computers, but they are also integrated with cameras, LiDAR, GPS, magnetometers, and accelerometers, again of capabilities unobtainable in such compact and digital forms until recently. We now have ways to collect data that we did not in the past. In his presidential address to the Geological Society of America, "New Technology; New Geological Challenges," Clark Burchfiel (2004) made a compelling case that the geological community must embrace new modes of data collecting. When Burchfiel gave his address, precise GPS measurements were revolutionizing active tectonics and opening entirely new avenues of research. Today, developing and adopting new mobile technology can advance our ability to perform basic geology at the individual level, beyond the unprecedented connectivity.

GSA has led the charge for mobile computing and mobile devices in field geology and geology in general. Just looking at the last few years of *GSA Today* shows the Society and its members' emphasis on using phones and tablets in research and education, with articles about virtual rocks by De Paor in 2016, augmented reality by Bursztyn et al. in 2017, and data collection from images by Glazner and Walker in 2020. *Geosphere* has also become an outlet for much information on mobile devices and geology (Pavlis et al., 2010; Walker et al., 2019). GSA and its members are developing applications and best practices for collecting data in the field unobtainable with earlier technologies.

Another enormous influence on how we work is the move toward open access (see the impact on GSA [GSA, 2020]). Scientists of all kinds are under pressure to make their data and papers available to the general public and other scientists. This pressure is intensifying and, shortly, will fundamentally change how we work with journal articles, whatever those turn out to be in the future.

Although the access to consume information and data will be open, we must remain vigilant that the science we produce is vetted and reliable. Publishing scholarly articles is a process that GSA does well, and our journals are respected and provide trusted information. Much of this is based on the peer-review process. It is tempting in the online world to post information before it is ready or reviewed. All data online look alike to the person who is not a trained scientist or does not appreciate the scientific method. Even experienced scientists may have difficulty separating the wheat from the chaff.

Our ideas and conclusions must be open and rely on a careful review process before they are "published." Furthermore, published today and in the future no longer means showing up in your mailbox in a magazine. Although anyone, anywhere can post an article online, those connected with GSA should remain of the highest quality.

We should not fear airing controversial and challenging ideas if well-posed. On the other hand, we should not give refuge to those wanting to publish wrong or incorrect findings. GSA cannot become an online avenue for climate change or evolution deniers to peddle misinformation and lies. It is ok to say something is incorrect based on our methods and judgments as scientists.

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SOME GUIDING PRINCIPLES AND IDEAS

What are some of the needs to move forward with online information and preserve it through GSA? GSA is doing an excellent job of making its members' work available. These contributions are at the heart of what the Society is about. We have established paths for open access for our journal articles. Along with the papers, though, we have to view the underlying data and observations as essential resources. It is being able to put our hands on the combination of ideas and the data presented by researchers that forms the infrastructure of much of modern science. We view this as a cyberinfrastructure that forms the highways for data and the onramps and offramps for ideas.

Let's start by considering the primary data we collect, whether it is samples, maps, or measurements. Again, my discussion is partly but not wholly referenced to field data. A popular way of talking about data is asking whether it is FAIR—findable, accessible, interoperable, and reusable. These qualities and the FAIR principle have been fully articulated and written down only in the last five years (Wilkinson et al., 2016) but have guided much of the way we work with information for a long time.

I think of the idea of FAIR in somewhat different terms using statements developed during NSF-funded workshops on cyberinfrastructure and geoinformatics in the middle 2000s. Out of one workshop about evaluating a national geoinformatics community organization came the following statements about the scientific and public needs surrounding data and publications.

I can't integrate what I can't find;

I can't use something I don't understand;

I don't want to use something I don't trust;

I can't use something that isn't there anymore.

I think these statements give FAIR a more human or individual level to scientists and anyone wanting to read or understand or use scientific data. These statements also cover all cases of using cyberinfrastructure for research or teaching or self-education. They represent the concerns of the typical user.

What should GSA be doing to address these concerns and be FAIR? We should look at our current activities as a professional Society in light of the statements made above. We must also remember that a lot of our science starts with field data and products and builds from there.

1. I cannot find it. Making information findable is a fundamental goal. We need to ensure that search results are thorough and relevant and as complete as reasonable. GSA may not lead in this aspect, but we already organize data and maps, and we contribute directly and indirectly to indexing by GeoRef and Google. Along with other societies and organizations such as the USGS, GSA must continue to make our products organized and well described.
2. I cannot understand it. GSA can take the lead by bundling resources for teaching and research, along with all its data and information. Such activities in the past were singled out as education and outreach but should be integrated into publications and searches. This is an extra effort but can expand the reach of our scholarly products.
3. I do not trust it. GSA is in an excellent position to deal with trust because it is known for its peer review and publications. We cannot rest on these accomplishments but must build to the future with data-reporting standards with an eye for reusing data in the future. GSA should be a leader in setting community standards for data reporting. In that way, we serve all needs, and the GSA imprimatur assures the highest quality.
4. Data and information disappeared. This is always an area of worry that stems from the fact that no one wants to be responsible for keeping data in perpetuity (whatever that means). Some of the mechanics behind this should not be a concern. We accept on a daily basis that cloud technologies make it possible to preserve our very important information. There is also a worry about whether the data will be readable in the future. However, this seems less of a problem now that we have serialization protocols like JSON and GeoJSON that should be long-lived and easily parsed. We can deposit code and data structures in places like GitHub and schema.org.

However, geology is different from other sciences in that a critical component of our data is knowing *why* it was collected; we can call this the purpose. We collect data and make observations for some reason. Any specific purpose will mean that there will be some bias in data collection. For example, I was asked by a friend in grad school who was studying engineering whether I had a picture of jointed rocks. I did not remember at the time ever taking one, but told him I would look. It turns out that every picture I had taken as a geologist was of jointed rocks. GSA can take the role of understanding this observation and filtering bias. Considering a study's purpose leads to a fifth statement:

I need to know why these data were collected.

Our activities for these five statements must not be limited to just field data and studies. GSA should be willing to take the lead in almost any area of geology. GSA has a scientific Division structure that is suited to this purpose. We have Divisions for structural geology and tectonics, geoinformatics, sedimentary geology, and geochronology, to name a few. These groups can and should take the leading roles on *trust*, *understanding*, and *purpose*. GSA can team with other organizations to make things *findable* and *preserved*.

What are the most problematic aspects of the process and these activities? The first is finding a way to maintain what you have, and we will call this sustainability. The second is knowing when you have done enough. GSA can play a pivotal role in addressing both issues.

Sustainability is a fundamental problem. As a learned society, how do we preserve our efforts and keep our data for a long time in the online world? This is not worrying about storage and retrieval minimized by cloud resources, standard protocols for electronic storage, and robust data structure formats, but is the process's organizational oversight. Two things are necessary: Someone has to keep attentive to storing the information, and some group needs to ensure that the standards for data reporting change as the science and reasons for study change. GSA can take a leading role in these. We have published the *Geological Society of America Bulletin* for the past 133 years. Surely we can contemplate keeping electronic resources going for the next few decades. Just as we did not print our journals in-house, we will not store our information in-house but will work with experts in the field dedicated to this goal. GSA members organized under the scientific Divisions can keep up with cutting-edge data collection and reporting needs in different fields. This is essentially part of the peer-review process but could be taken on more fully and explicitly by the Society.

So who pays for storage and maintenance? Cost is always the most pressing question and one that has not found a good answer. At present, the National Science Foundation is funding research on preservation, interoperability, and community engagement in its EarthCube program and building cyberinfrastructure in computer sciences. While these programs foster cutting-edge scientific and engineering developments, they are not scalable or sustainable for long-term efforts. That is not their mission. GSA can lead those efforts. Through its membership, its status as a professional organization, and its nonprofit foundation, we should develop a strategy for long-term sustainability.

This does not mean that GSA pays for all of the efforts. Instead, *can* we foster leadership with other groups to move forward, much in the way that the GeoScienceWorld effort was spearheaded by GSA and AAPG and has changed the way the Society monetizes its publications? The final result will almost certainly be some sort of private-public or non-profit–for-profit partnership. This model works well for other infrastructures, like highways and utilities, and nonprofit organizations like GSA and companies like Brunton. We will not know how to do this or what it will look like until we try.

The second is knowing when to stop. In this, I am reminded of the saying, "perfection is the enemy of good" (Voltaire [1764], *in* Ratcliffe [2011]). In the case of data and reporting it, perfection can become a barrier to any progress. Geology and its descriptions are based on words. Words mean things, but they can mean very different things to different people. In our case, the Pareto principle or 80–20 rule means that 80% of our effort is explained by 20% of our terms. We can never capture every sense in which a word has been used. Our best path is to figure out how terms are mostly used. Terms are metadata in many ways, and usage is at the heart of trust and understanding. It is a basis for being FAIR. Knowing how words are used also rests in understanding why someone collected the data in the first place. GSA should be *the* international professional association that works with the earth sciences community on this critical metadata and articulates the ontologies that reflect the science's meaning and context.

INTENDED AND UNINTENDED CONSEQUENCES

The online world is where we are going to live and work. Embracing this reality and recognizing that mobile devices will be used increasingly in the field for data collection and knowledge summary will build much better science. Some of the best intentional outcomes of this are clear and important.

1. We can make our research more repeatable and transparent. Access and rich data collection will allow anyone to examine field relations or all of the thin sections or models used by a researcher. All field observations can carry location information and images, thereby giving full context and content.
2. We can engage the citizen scientist. As has already been done in many fields, we should bring the citizen scientist into our work. Some geology can undoubtedly be crowdsourced, and engagement makes our science more real and less intimidating. What would happen if we crowdsourced the modal compositions of rocks, with data preserved and reviewable, using a mobile app such as StraboTools?
3. We can better get reliable information to the general public. We can use open-access journals and open data to showcase our science to the public and bring our field experiences to them. This way, nothing is hidden or unrevealed. Full access may make consuming and appreciating science more attractive and palatable to the public.

Working with citizen scientists and the public is where we have great opportunities. Modern science seems mysterious and daunting. Just 50 or 100 years ago, you could get out of high school, understanding much of the basic science and math for how you lived, and know how things worked from a light bulb to a car. Ordinary people could fix a car. This ability made science open, transparent, real, and very relevant. Now we deal more with computers, and the basic workings of things are harder for the public to grasp. We have gone from lenses, film, and photographic paper to computers and data storage. Indeed, images today use concepts such as the Fast Fourier Transform and data processing of sparse matrices, subjects developed only in the last few decades. Understanding digital images requires the physics and math most folks take after their freshman year in college. This reality makes even simple, everyday tasks difficult to understand by most people. Opening our science will allow others to peer deeper into and understand better what we do. By exposing our work, perhaps we can make inroads to understanding and trust by the public.

Technology and online geology are also a way to enhance access, diversity, and inclusion by relying less on or modifying the field setting. In an excellent paper in *GSA Today* this September, Whitmeyer et al. (2020) gave compelling examples of how living in the online world and using mobile technologies can vastly expand access and inclusion. Our science's quality increases immensely with such efforts and can be taken to groups previously excluded from field research. The techniques developed address accessibility and inclusion and make it possible to share and involve anyone interested in field geology, showing them the richness displayed by rocks, sediments, volcanoes, and geomorphology from the field. We should be able to foster the broadest possible participation regardless of the setting.

Not only are persons with disabilities poorly served by many of our activities, but so are Black, Indigenous, and People of Color. The geosciences lag significantly in the inclusion of People of Color in its disciplines. Some of this indeed resides in the emphasis on field geology and fieldwork so proudly and prominently displayed on our website and in our publications. While many of us, including me, are lured by the field and find it compelling, it is a hard sell to individuals who may be unsafe in remote and rural settings because of the color of their skin. Changing the safety aspect is something we are all responsible for but will take tireless and longtime work. However, changing the way field data and fieldwork becomes available is something we can and must do now (Anadu et al., 2020). Mobile technologies and online geology are a way to abolish these limits and make our science accessible to anyone.

SUMMARY

The Geological Society of America should seize this opportunity to lead the earth sciences forward with online efforts centered on scientific data and rigorous analysis. Creating an online community is a broad subject and requires us to participate in a wide range of activities. First, we must produce understandable and widely available outreach materials and couple them with our scholarly products. Second, through continued efforts at peer review and understanding reporting standards, our data and interpretations must continue to meet the geological community's requirements. Third, our work must be widely and seamlessly available through open access and open data (Bolukbasi et al., 2013). Last, we must preserve our efforts for future use and reuse by devising a funding and partnership model for the long-term preservation of digital information. In these ways, we can provide relevant, complete, and fact-based information to all curious and interested persons.

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