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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:

- Full implementation of integrated, coordinated, open, and networked (ICON) science principles will foster more multidisciplinarity and science literacy
- Databases are a key component to initiating and maintaining ICON practices
- Data sharing should be expanded outside of the immediate science community

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Tectonophysics Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science

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Abstract This article is composed of two independent opinion pieces about the state of integrated, coordinated, open, and networked (ICON) principles (Goldman et al., 2021, https://doi.org/10.1029/2021EO153180; Goldman et al., 2022, https://doi.org/10.1029/2021ea002099) in *Tectonophysics* and discussion on the opportunities and challenges of adopting them. Each opinion piece focuses on a different topic: (a) global collaboration, technology transfer and application, reproducibility, and data sharing and infrastructure; and (b) field, experimental, remote sensing, and real-time data research and application. Within tectonophysics science, ICON-FAIR principles are starting to be adopted and implemented, however they have not become frequent and there are still plenty of opportunities for further development. During the last decade, standardization reduced fragmentation, facilitated openly available databases, and enabled different modeling methods to be combined. On the other hand, integration and coordination remained insufficient as exemplified by numerous geophysical interpretation programs running on different platforms, lacking the proper documentation and with diverse output formats. We agree that adapting the principles of ICON-FAIR brings high efforts and risks, but in the end, it has great benefits and potential in the tectonophysics community.

Plain Language Summary The task of understanding complex geologic events and concepts such as earthquakes, faults, and tectonic plate interactions, requires collecting data from diverse sources; thus making science that is integrated, coordinated, open, and networked (ICON science) is vital to the research, discovery, and forecasting of Earth scientists. Here, we assess the state of ICON principles within the Earth Science sub-field of tectonophysics, and determine where aspects of ICON science are being put into practice at various levels and how we might improve the use of ICON principles in the future.

1. Introduction: Why Should We Always Be Thinking About ICON in Our Research?

Scientists in Tectonophysics use multidisciplinary approaches to investigate monitoring networks, experimental laboratories, and data centers that collect and store an enormous quantity of data. Therefore, **making science that is integrated, coordinated, open, and networked (ICON science)**, is vital to research, discovery, and forecasting. However, ICON has not yet become a frequently used term in Earth Science, and yet there are currently aspects of ICON science that are being developed and promoted within the field.

If the whole scientific community could easily use all of the geological and geophysical information in the world, models produced would be more complete, and we could overcome the limitations of the techniques used independently. As a consequence, risk forecasting models would be more reliable and effective in mitigating the hazards posed by Earth's dynamism.

The collaborative opportunities from fully implementing ICON approaches would be enormous. Imagine networked groups partnering to gather samples and data from remote or far away locations and regions with instrumentation resources helping scientists from those areas with less access to those facilities. ICON science could lead the way in fostering more efficient, economic, collaborative, and inclusive sample or data collection that could arise from such a network. Achieving full implementation of ICON science would also enhance global science literacy and a commitment to scientific research that matters to the public.

Here we discuss the current status of ICON practices and implementation in the sub-field of **Tectonophysics** in terms of both data sharing and infrastructure as well as applications in field and experimental research. We highlight where ICON is being put into practice and where we need to strengthen our efforts to incorporate ICON science in **Tectonophysics**. We end with some **suggestions** to move forward and a call to action for researchers and educators alike.

2. Global Collaboration, Technology Transfer and Application, Reproducibility, and Data Sharing and Infrastructure

The current status of bringing ICON practices into the field of Tectonophysics involves efforts to establish databases with standardized reporting protocols and hosting converging conferences.

2.1. Current Status and On-Going Efforts

We outline the on-going efforts in two distinct research areas in tectonophysics toward ICON science: (a) global databases for geochronology, geochemistry, petrology, mineralogy, the standardization and reassessment of the global heat flow database; and (b) biennial conferences bringing together analog and computational tectonic modeling.

Tectonophysics aims to understand the mantle and lithospheric processes that shape our planet. This field integrates geophysical, geological and geochemical data from both quantitative studies (model simulations and experiments) and field observations. Therefore, a vast variety of individual databases exists among the different subdisciplines such as geochronology, heat flow, and geochemistry; and in many cases, they lack standardized protocols and quality control or use different methodological approaches. In recent years, efforts toward ICON science in distinct research areas in tectonophysics have been made to agree on concentrating and integrating data, standardized protocols and quality criterias. Furthermore, biennial conferences bringing together analog and computational tectonic modeling strengthen the knowledge transfer between disciplines.

An example of an active ICON initiative is EarthChem, a community-driven, NSF-funded, portal for multiple disciplines, whose purpose is to integrate different databases into one portal, offering free data access to researchers, publishers, funding agencies, educators, and students (Figure 1). In doing so, they support networking by grouping the data, and aiming to build communities around specific themes, so, although there is no reference that focuses on "best practice" these research communities can build such best practices focused on data management and open data sharing, another of the ICON science characteristics.

In the case of the Global Heat Flow Database (Figure 1), for example, the different industry collaborators provide thermal data which is then reviewed, digitized, and coordinated under one project, led by academia, to develop an accurate data set for multidisciplinary use. Moreover, the industry funds through R&D research projects within the heat flow community to better understand thermal processes and actively participates in ongoing research and publications. The database is currently in the process of transformation into a modern database framework. The database was reviewed last year in terms of structure and quality criteria by scientists experienced with heat flow data (Fuchs et al., 2021). This agreement builds the basis for the on-going reassessment of the database.

Converging conferences must be among what the communities can do with coordinated and integrated data such as EarthChem. Although not directly targeting the use of EarthChem, an example of the converged conferences can be found in the field of tectonic modeling. Analog and numerical modeling are two major research methods in tectonic modeling, a research area in tectonophysics aiming to understand the origin and long-term evolution of structures of crustal to lithospheric scale through modeling. Although founded on the same governing equations and rheologies, the two modeling methods are known for the alarming degree of discrepancy in the results even for the same model setup, which prompted tectonic modelers to enhance consistency by learning from each other. Two conferences are notable in this line of efforts: analog modeling for Tectonic modeling (AMTP) workshops and GeoMod. AMTP is a biennial international workshop organized by the US-based analog and numerical modelers in tectonics, structural geology, and computational geodynamics. AMTP was inspired by GeoMod, which is also a biennial international workshop organized by European researchers. As further discussed in the next section, these conferences suggest challenges and opportunities in enacting the ICON principles.

Database / Infrastructure	Data / Information commonly used by the Tectonophysics community
National Geologic Map Database (ngmdb: USGS) https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html	• A catalogue of published geologic maps in the U.S.
ORFEUS (Observatories and Research Facilities for European Seismology) https://www.orfeus-eu.org/	• European Infrastructure for seismic waveforms, providing digital, broadband seismology data in the European-Mediterranean area
NAVDAT (North American Volcanic and Intrusive Rock Database) https://www.navdat.org/ ***EARTHChem*** https://www.earthchem.org/	• Web-accessible repository for age, chemical, and isotopic data from Mesozoic and younger igneous rocks in western North America and used for data preservation, discovery, access, and visualization of geochemical, petrological, and mineralogical data
EMSC (Euro-Med Seismological Centre) https://www.emsc-csem.org/#2 ***ANSS*** (Advanced National Seismic System: USGS) https://www.usgs.gov/natural-hazards/earthquake-hazards	• Latest information on recent earthquakes worldwide
OpenTopography https://opentopography.org/	• High-Resolution Topography Data and Tools
EFEHR (European Facilities for Earthquake Hazard and Risk) http://www.efehr.org/en/home/	• Network of organisations and community resources aimed at advancing earthquake hazard and risk assessment in the European-Mediterranean area
WDC (World Data System) in Beijing http://www.geophys.ac.cn/	• Collection of magnetic, ionospheric, GPS data
Australia Geophysical Data Collection https://data.gov.au/data/dataset/australian-geophysical-data-collection	• Comprehensive publicly available Australian airborn magnetic, gamma-ray, seismic, electromagnetic, and gravity data sets
National Geochronological database (USGS) https://mrdata.usgs.gov/geochron/	• Compilation of Radiometric and fission-track age determinations of geologic materials from the continental US and Alaska
Quaternary Fault and Fold Database (USGS) https://doi.org/10.5066/F7S75FJM	• Information on faults and associated folds in the United States that demonstrate geological evidence of coseismic surface deformation in large earthquakes during the past 1.6 million years (Myr).
The Global Heat Flow Database maintained by the International Heat Flow Commission (IHFC) http://www.ihfc-iugg.org/products/global-heat-flow-database	• A collaborative project between international academia and industry that aims to support the process of understanding the Earth's thermal structure by providing authenticated heat flow and thermal properties data.

Figure: *Some examples of existing resources for sharing data worldwide and meeting aspects of ICON . Also, stay tuned for EPOS , a pan European infrastructure for sharing solid earth science data, observations, and research results (https://www.epos-eu.org/). EPOS service to the user community is expected to start in the Operational Phase after 2023.*

Figure 1. Some examples of existing resources for sharing data worldwide and meeting aspects of ICON. Also stay tuned for EPOS, a pan European infrastructure for sharing solid earth science data, observations, and research results (https://www.epos-eu.org/). EPOS service to the user community is expected to start in the Operational Phase after 2023.

2.2. Challenges and Opportunities of Implementing ICON

The incipient and anecdotal efforts introduced in the previous section have yet to gain widespread support and adoption across many research communities in tectonophysics. In this section, we identify challenges and opportunities in disseminating ICON science.

2.2.1. Integration

ICON initiatives encourage the integration of processes across traditional disciplines in different spatial and temporal scales (Goldman et al., 2021). We understand this as the need for boosting the spatio-temporal transdisciplinarity from these three main sciences, which requires overcoming the challenge it includes. As an example, the thermal data are published in repositories for different research areas (e.g., Geology, Geophysics, Biology, etc.). However, each of the disciplines pursues only part of the data and therefore a global standardization protocol is required in order to create a common database structure. As well, the integration of analog experiments and numerical simulations has low demand and obscure feasibility. Even AMTP and GeoMod aim to enhance coordination of the two research methods and improve reproducibility but not to integrate them. However, since the communities participating in those conferences are open to integration with seismology and geomorphology, room for integration is ample. Desired is the leadership that can set and prioritize realistic goals and organize community-wide efforts to achieve them.

2.2.2. Coordination

The use of different equipment to obtain data during the last decades evolved continuously, as well as methods and algorithms to estimate parameters. Also growing is the call for coordination: that is, consistent protocols and their uses to ensure methods and data to be interoperable across disciplines. However, uncertainties still vary, which makes a comparison of data quality sometimes difficult, varying its success from discipline to discipline. For example, the lack of coordinated efforts to share experimental and simulation data across the analog and numerical modeling communities was the very motivation for AMTP. The previous outcomes from AMTP and GeoMod workshops have revealed the major sources of discrepancy in model results (Buiter et al., 2016; Reber et al., 2017; Schreurs et al., 2016). However, the ways to remove those identified sources have yet to be formulated in a systematic way.

The agreement on the heat flow database standardization opened new ways to compare and characterize the individual data entries and created a better idea of data reliability and quality. The review of the database is a collaborative work open to each scientist. The newly established protocols and methods initiated further programs that were coordinated by different task forces. Each of these task forces are responsible for coordinating parts of the database and are organized throughout the heat flow community, with the goal of more collaboration and improvement in quality of the generated data resulting from the consistency of the global database.

2.2.3. Open

There are still a few challenges to overcome in terms of openness. With journals, for example, obligating authors to make data available is a step forward but not all researchers/institutes are given access to the data. Some have personal reasons like the concern of sharing data before publishing, while others are constrained by funding regularities like industry or political restrictions.

The tectonic modeling community started perceiving openness in research methods and data as a practical way of advancing science and a service to society. For instance, AMTP Workshop 2020 collected all the submissions for plenary and poster presentations and distributed them using the data repository service, figshare.com. Extensive use of such online services and affordable cloud storage would ensure community activities to be FAIR (Wilkinson et al., 2016).

An outstanding challenge is how to identify and disseminate the best practices across the diverse communities in tectonophysics. Active promotion of the existing protocols and software tools that share goals with ICON science might be a good start. For instance, it would be beneficial for tectonic modelers to assess a rubric developed by the EarthCube Research Coordination Network project "'What about model data?' Determining best practices for preservation and replicability" (https://modeldatarcn.github.io/). Designed to provide simulation data management best practices, the rubric directly addresses the motivation of AMTP workshops. Also, well-structured and financially well-supported groups could take the lead in distributing data and experimental protocols through their existing networks or by expanding them.

2.2.4. Network

The construction of open-access databases in Tectonophysics reflects one of the steps this field is taking into providing open access to data that has been privately compiled in the past through better communication using workshops and networking. When open data, software, and models are exchanged through networks of various scopes, the discriminating effects from the financial discrepancy will be mitigated. Nevertheless, individual research disciplines still need to strengthen their communication in terms of collecting data. Not only data of specific interest to an individual sub-field but also additional data for potentially broader interest should be collected to satisfy the protocols of the database and therefore a broader usage for the entire community.

Despite this, the panorama is satisfactory when taking a look at the increase in the number of individual database users. For example, the available statistics of data usage in the EarthChem database portal (https://www.earthchem.org/about/statistics/ecl-statistics/) show that from May 31, 2012 to May 31, 2019, there was an increase in data download numbers which correlates with the number of data submissions to the portal. This statistic demonstrates that in the last decade there has been an increasing interest in the use of databases such as this one. Another beneficial impact of exchanging open data through networks of various scopes is the mitigation of discriminating effects from the financial discrepancy between countries and irregular geopolitics.

3. Field, Experimental, Remote Sensing, and Real-Time Data Research and Application

ICON principles have also begun being implemented in applied research fields of tectonophysics. However, the community is in need of a push to incorporate ICON science more consistently such that it becomes second nature.

3.1. Integrated

Integration often occurs in the field or lab through collaboration between researchers and projects that apply other aspects of traditional sub-disciplines. In fact, as of 2019 IRIS and UNAVCO (Incorporated Research Institutions for Seismology and University NAVSTAR Consortium) have joined forces to better support research and education in geophysics. However, many processes are not always commonly integrated and people in different disciplines approach field or lab experiments quite differently such that working collaboratively to bring together different sub-disciplines in a coordinated effort is often overlooked or daunting because of the unknown factor related to how others do similar work or even that others run through similar processes. For example, there are numerous programs used for geophysical data interpretation which are often based on different theoretical assumptions, run on different computer platforms and have diverse output formats.

3.2. Coordinated

There is an effort being made to coordinate data through databases and organized systems, however, such coordination is usually focused on a single country or region, rather than a global effort (Figure 1). Additionally, several manuscripts have been published in scientific journals, for example, in the realm of thermochronology, advocating for organized protocols when it comes to data reporting, outlier flagging, or data modeling decisions (e.g., Abbey et al., 2020; Flowers et al., 2015; Flowers & Kelley, 2011; Murray et al., 2020; Sousa & Farley, 2020).

3.3. Open

Although new data, software, and/or models are published and often made fully public, they are not often well advertised or are unequally advertised. For instance, researchers will often create a tool, publish it in a manuscript, and provide a link to an accessible site like GitHub. And yet, very few people know about or use the tool, and in fact a few years later another researcher will remake something very similar. In addition, these available resources commonly lack user guides or manuals that help explain how and when to use the new items. Consequently, researchers often end up re-creating similar resources.

3.4. Networked

Historically, there were very few networked efforts in the field. The only time we see such collaboration is between well-established partnerships and usually involves one or two colleagues helping out one or two other colleagues. However, despite the relatively poor collaboration among scientists in the field of tectonophysics, there are presently several different citizen science projects developing that are beginning to involve the public in research, such as LastQuake, Participatory Lithology, Romania Geomagnetic Map, the National Map Corps, and Tweet Earthquake Dispatch. Results of these experiences (Bossu et al., 2018; Young et al., 2013) evidence that in addition to raising public awareness in areas such as risk reduction and geo-conservation, these techniques provided access to large amounts of new data both spatially and temporally, that would otherwise have not been possible to achieve by single projects or organizations alone. This is a straightforward example of the potential benefit of ICON science on earth sciences.

4. Bringing ICON in as Second Nature

Here, we emphasize some key challenges to implementing ICON principles in tectonophysics and put forward possible solutions as lists of top-down and bottom-up actions.

Some key challenges to implementing ICON principles in tectonophysics include:

1. The desire of each researcher to share their research and lose the *prima donna attitude* especially characteristic of the former generations (affects openness and integration)
2. Finding methods, formats, and styles that everyone can agree on (affects openness, integration, and coordination)
3. The time and effort spent on loading the data onto the maintained shared data sites (affects coordination, openness, and networking)
4. Maintenance of the shared databases, and making sure people are using them correctly and that new data is navigable and searchable after it has been loaded (affects coordination and networking)

Possible solutions or beginnings to solutions might include top-down actions like:

1. Required training on data sharing (and workshops). Many research institutions and organizations already require training on scientific merit and integrity, so they could add a component on how to report and share new data and models through maintained infrastructure and databases
2. Providing incentive. Approved databases could have some form of credit that can be used to track individual contributions, for example, citable DOI's providing recognition for data contribution in addition to article publications. This is beginning to take hold as repositories like Zenodo and EarthChem add citable doi information connected to data
3. Fostering the careers of researchers and laboratories, especially early career scientists, which promote ICON practices
4. Encouraging infrastructures to follow ICON principles through financing implementation costs from national or international research calls

On the other hand, bottom-up ways to disseminate ICON ideas could involve:

1. ICON sessions during international congresses or annual meetings
2. Creating clear guidelines and instructions on maintenance and contribution to data collections
3. Using publications to establish new data reporting protocols
4. Organizing university lectures and/or lessons for students

5. Call to Action: Tectonophysics Can Embody ICON! Here Is Where We Begin

Recently, journals (e.g., Tectonics: AGU) have begun to require that all data associated with a submitted manuscript must be housed in a database. More journals should adopt this requirement and focus on publicly accessible databases, they could (a) define ICON, (b) explain why this is a new and good practice and why they support

ICON, and (c) provide a list of the existing open and shared databases, perhaps compiled from this collaborative special publication, with links to them.

As researchers, we can be more transparent about the data we are collecting. Sending out a call to established listservs to see what similar data already exists will not only begin the process of networking and integration but can aid in coordinated efforts to consolidate and elaborate on existing data. Additionally, connecting with local communities while doing research or collecting data could spark relationships to begin a networked campaign with the public.

Finally, it should be our personal commitment, as contributors to this ICON science special publication, to briefly introduce the topic at all future workshops, meetings, and congresses in which we participate.

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