Artificial intelligence and plate tectonics

Compiled by Claudio Bartolini

Editor of Revista Maya

Artificial intelligence (AI) and machine learning are revolutionizing plate tectonics by building complex Earth models, simulating plate movement faster, analyzing ancient zircon crystals to date the start of tectonics to over 4 billion years ago, and improving earthquake prediction by identifying patterns in seismic data for large, sudden slips. AI helps decode Earth's history, understand current geological processes like subduction, and potentially forecast major seismic events by processing vast datasets beyond human capability, linking deep Earth dynamics to surface phenomena like mineral deposits.

Key Applications of AI in Plate Tectonics:

Modeling Earth's Dynamics: AI builds intricate models to simulate plate movement and boundary evolution, helping understand climate, resources, and Earth's history.

Accelerating Simulations: AI algorithms speed up simulations of fault slips (sudden shifts) by factors of 75x or more, using supercomputers to tackle complex physics.

Deciphering Ancient Earth: Machine learning analyzes ancient zircon crystals to find evidence that plate tectonics started much earlier (over 4 billion years ago) than previously thought, influencing early land formation.

Predicting Earthquakes: AI models analyze seismic signals to predict ground motion and the timing of destructive stick-slip earthquakes (like caldera collapses), improving hazard assessment.

Identifying Tectonic Settings: Deep learning (like Convolutional Neural Networks) classifies tectonic settings more accurately by recognizing patterns in geophysical data, notes ScienceDirect.com.

Uncovering Hidden Controls: AI identifies novel features (e.g., related to deep subduction) that control large earthquakes, validating existing theories and finding new ones.

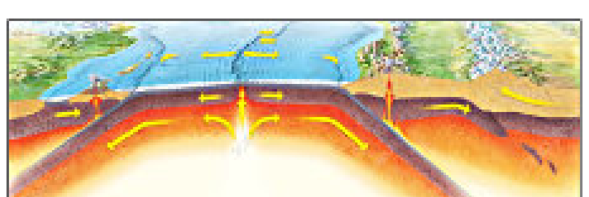
How It Works:

Data Analysis: AI processes massive datasets from GPS, seismic sensors, and geochemical analyses of ancient rocks (like zircons).

Pattern Recognition: Machine learning algorithms find subtle patterns in data (e.g., seismic patterns before a quake, geochemical signatures in minerals) that humans or traditional methods might miss.

Predictive Modeling: AI creates sophisticated models to predict future geological events and understand past Earth processes.

In essence, AI provides powerful tools to model the complex, long-term evolution of Earth's tectonic system, offering deeper insights into its past, present, and future.



Confidence at every stage – How AI is transforming the geological workflow

Victor Cha MAusIMM, Product Strategy Manager – Exploration, Micromine.

As the mining industry continues to evolve, so do the expectations placed on geologists.

While the geology itself hasn't changed, the way decisions are made has. Geological modelling is now a more data-driven and less empirical process, shaped by larger datasets, tighter exploration budgets, and growing pressure to do more with less. Geologists are expected to deliver confident decisions faster and with fewer resources. In this environment, artificial intelligence (AI) - particularly machine learning and neural networks - has emerged as a powerful ally in navigating complexity and supporting better decision-making at every stage.

https://www.ausimm.com/bulletin/bulletin-articles/confidence-at-every-stage--how-ai-is-transforming-the-geological-workflow/

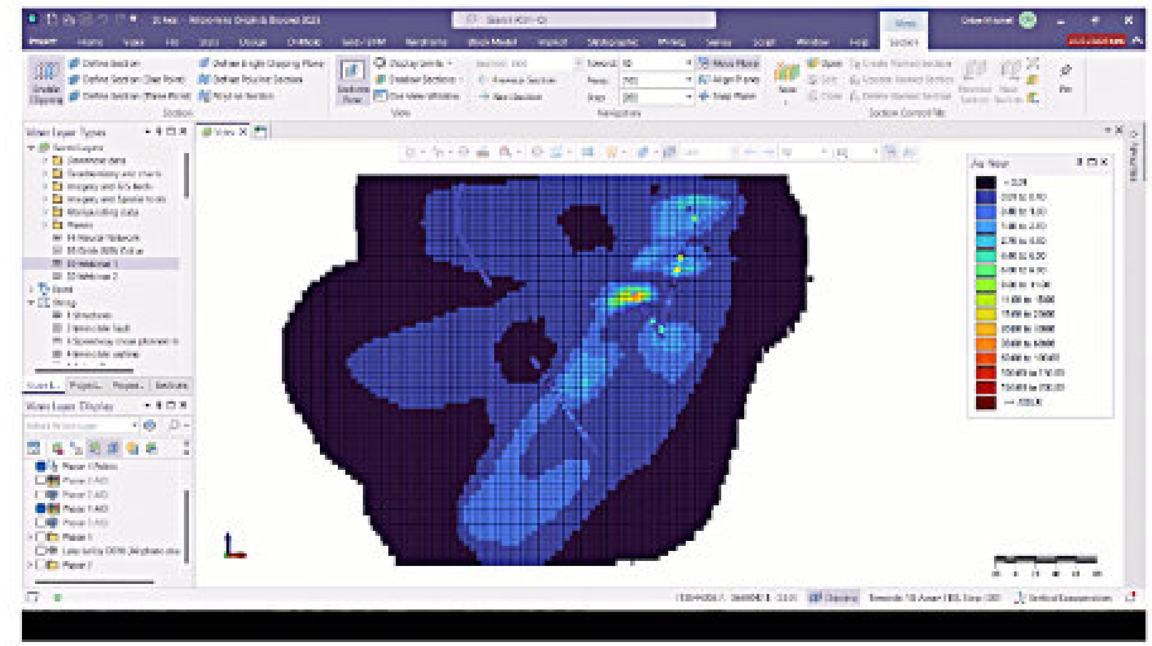


Figure 1: High-grade trend dipping southwest, identified using Micromine Origin Grade Copilot.

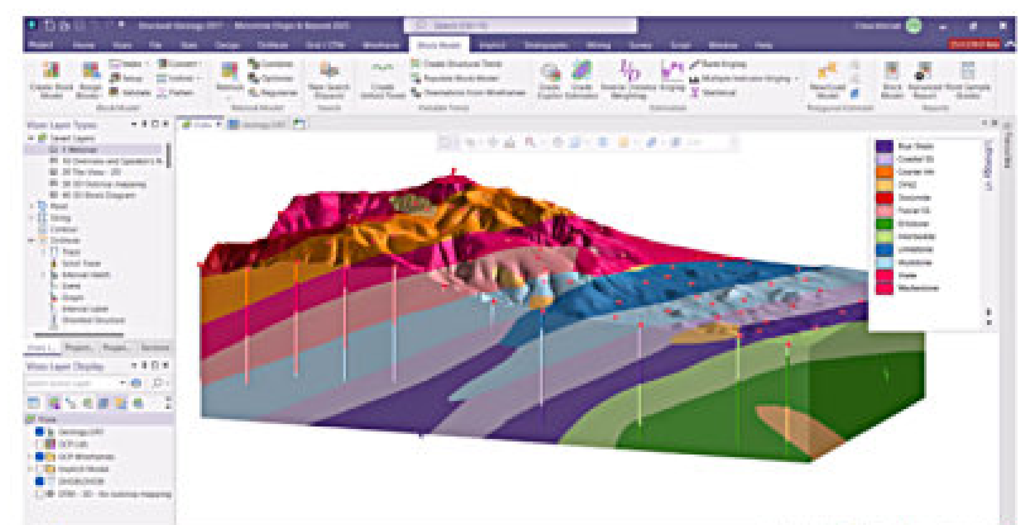


Figure 2: Lithology interpretation generated in minutes with Micromine Origin Grade Copilot.

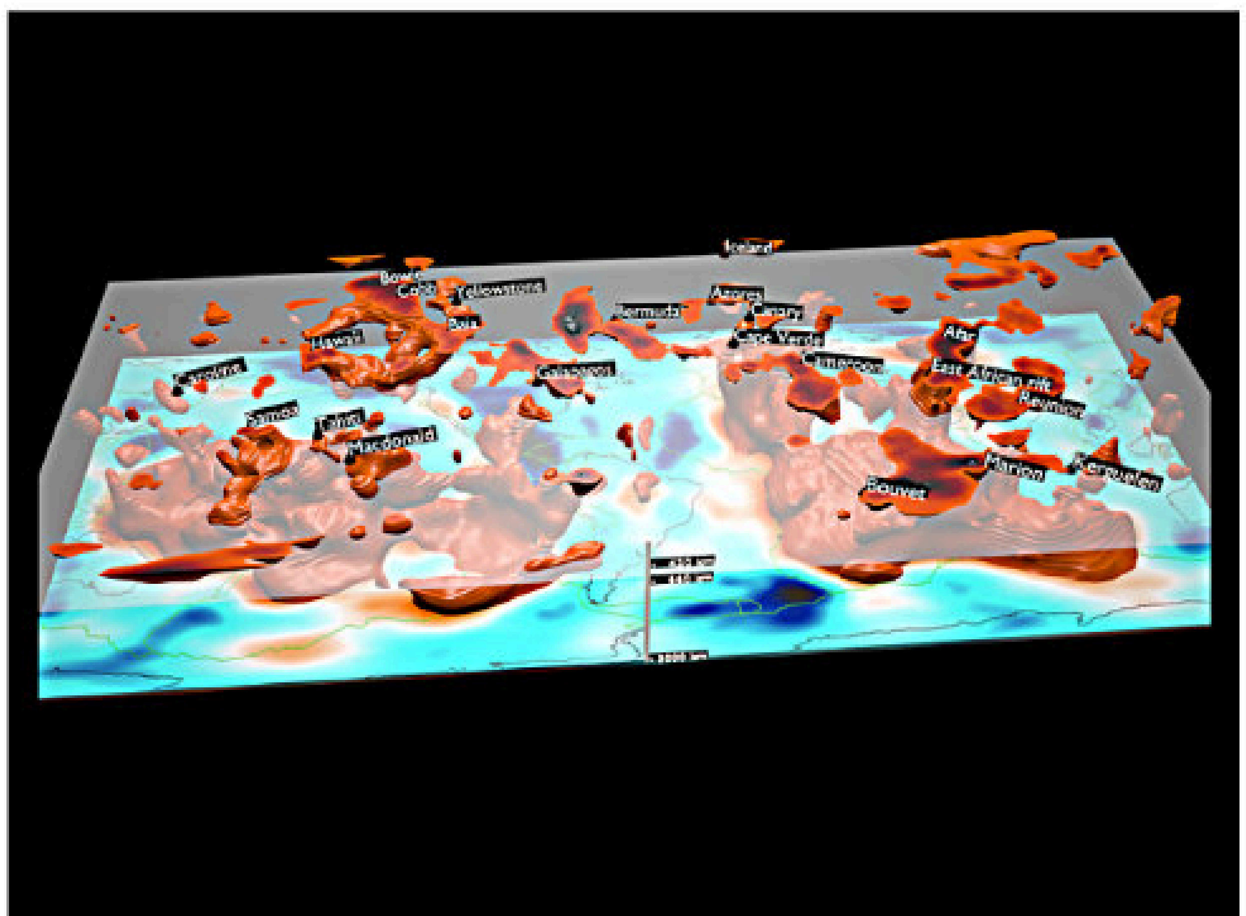
A Tectonic Shift in Analytics and Computing Is Coming

Artificial intelligence combined with high-performance computing could trigger a fundamental change in how geoscientists extract knowledge from large volumes of data.

More than 50 years ago, a fundamental scientific revolution occurred, sparked by the concurrent emergence of a huge amount of new data on seafloor bathymetry and profound intellectual insights from researchers rethinking conventional wisdom. Data and insight combined to produce the paradigm of plate tectonics. Similarly, in the coming decade, a new revolution in data analytics may rapidly overhaul how we derive knowledge from data in the geosciences. Two interrelated elements will be central in this process: artificial intelligence (AI, including machine learning methods as a subset) and high-performance computing (HPC).

Already today, geoscientists must understand modern tools of data analytics and the hardware on which they work. Now AI and HPC, along with cloud computing and interactive programming languages, are becoming essential tools for geoscientists. Here we discuss the current state of AI and HPC in Earth science and anticipate future trends that will shape applications of these developing technologies in the field. We also propose that it is time to rethink graduate and professional education to account for and capitalize on these quickly emerging tools.

https://eos.org/science-updates/a-tectonic-shift-in-analytics-and-computing-is-coming#:~:text=More%20than%2050%20years%20ago,on%20these%20quickly%20emerging%20tools.



A Cartesian representation of a global adjoint tomography model, which uses high-performance computing capabilities to simulate seismic wave propagation, is shown here. Blue and red colorations represent regions of high and low seismic velocities, respectively. Credit: David Pugmire, Oak Ridge National Laboratory

MAYA
REVISTA DE GEOCIENCIAS

Work in Progress

Great strides in AI capabilities, including speech and facial recognition, have been made over the past decade, but the origins of these capabilities date back much further. In 1971, the U.S. Defense Advanced Research Projects Agency substantially funded a project called Speech Understanding Research, and it was generally believed at the time that artificial speech recognition was just around the corner. We know now that this was not the case, as today's speech and writing recognition capabilities emerged only as a result of both vastly increased computing power and conceptual breakthroughs such as the use of multilayered neural networks, which mimic the biological structure of the brain.

Recently, AI has gained the ability to create images of artificial faces that humans cannot distinguish from real ones by using generative adversarial networks (GANs). These networks combine two neural networks, one that produces a model and a second one that tries to discriminate the generated model from the real one. Scientists have now started to use GANs to generate artificial geoscientific data sets.

These and other advances are striking, yet AI and many other artificial computing tools are still in their infancy. We cannot predict what AI will be able to do 20–30 years from now, but a survey of existing AI applications recently showed that computing power is the key when targeting practical applications today. The fact that AI is still in its early stages has important implications for HPC in the geosciences. Currently, geoscientific HPC studies have been dominated by large-scale time-dependent numerical simulations that use physical observations to generate models [Morra et al, 2021a]. In the future, however, we may work in the other direction—Earth, ocean, and atmospheric simulations may feed large AI systems that in turn produce artificial data sets that allow geoscientific investigations, such as Destination Earth, for which collected data are insufficient.

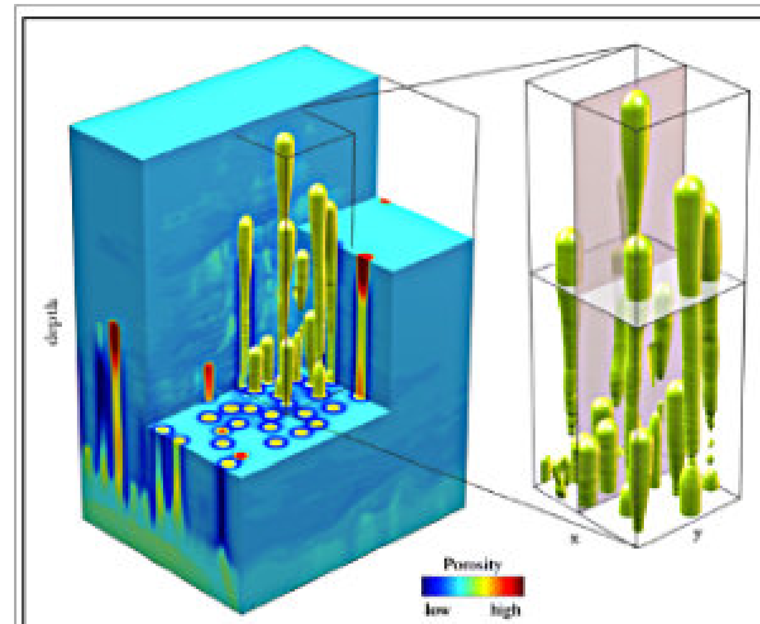
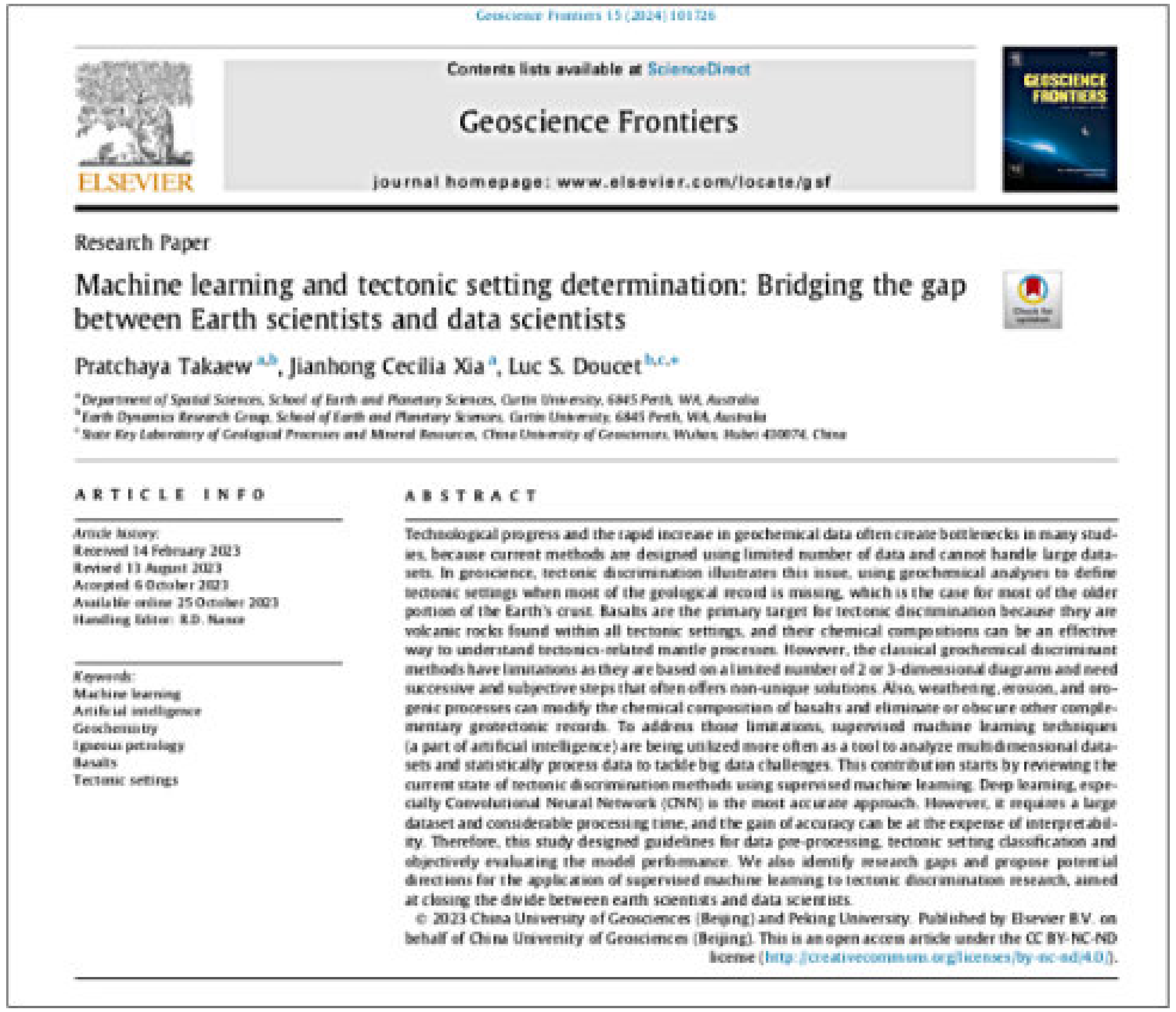


Fig. 2. A 3D modeling run with 16 billion degrees of freedom simulates flow focusing in porous media and identifies a pulsed behavior phenomenon called porosity waves. Credit: Räss et al. [2018], CC BY 4.0

https://www.sciencedirect.com/science/article/pii/S1674987123001937#f0040



Geoscience Frontiers 15 (2024) 101726

Contents lists available at ScienceDirect

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research Paper

Machine learning and tectonic setting determination: Bridging the gap between Earth scientists and data scientists

Pratchaya Takaew [a,b], Jianhong Cecilia Xia [a], Luc S. Doucet [b,c,*]

[a] Department of Spatial Sciences, School of Earth and Planetary Sciences, Curtin University, 6845 Perth, WA, Australia
[b] Earth Dynamics Research Group, School of Earth and Planetary Sciences, Curtin University, 6845 Perth, WA, Australia
[c] State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, Hubei 430074, China

A R T I C L E I N F O

Article history:
Received 14 February 2023
Revised 13 August 2023
Accepted 6 October 2023
Available online 25 October 2023
Handling Editor: R.D. Nance

Keywords:
Machine learning
Artificial intelligence
Geochemistry
Igneous petrology
Basalts
Tectonic settings

A B S T R A C T

Technological progress and the rapid increase in geochemical data often create bottlenecks in many studies, because current methods are designed using limited number of data and cannot handle large datasets. In geoscience, tectonic discrimination illustrates this issue, using geochemical analyses to define tectonic settings when most of the geological record is missing, which is the case for most of the older portion of the Earth's crust. Basalts are the primary target for tectonic discrimination because they are volcanic rocks found within all tectonic settings, and their chemical compositions can be an effective way to understand tectonics-related mantle processes. However, the classical geochemical discriminant methods have limitations as they are based on a limited number of 2 or 3-dimensional diagrams and need successive and subjective steps that often offers non-unique solutions. Also, weathering, erosion, and orogenic processes can modify the chemical composition of basalts and eliminate or obscure other complementary geotectonic records. To address those limitations, supervised machine learning techniques (a part of artificial intelligence) are being utilized more often as a tool to analyze multidimensional datasets and statistically process data to tackle big data challenges. This contribution starts by reviewing the current state of tectonic discrimination methods using supervised machine learning. Deep learning, especially Convolutional Neural Network (CNN) is the most accurate approach. However, it requires a large dataset and considerable processing time, and the gain of accuracy can be at the expense of interpretability. Therefore, this study designed guidelines for data pre-processing, tectonic setting classification and objectively evaluating the model performance. We also identify research gaps and propose potential directions for the application of supervised machine learning to tectonic discrimination research, aimed at closing the divide between earth scientists and data scientists.

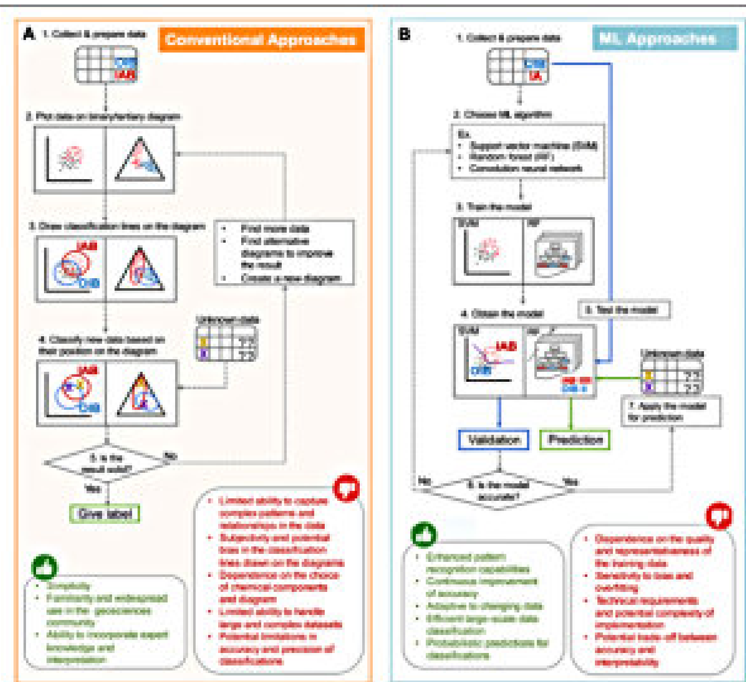


Fig. 1. Comparison between conventional tectonic discriminant workflow (A) and supervised machine learning-based analysis (B), where SVM stands for support vector machine and RF stands for random forest.

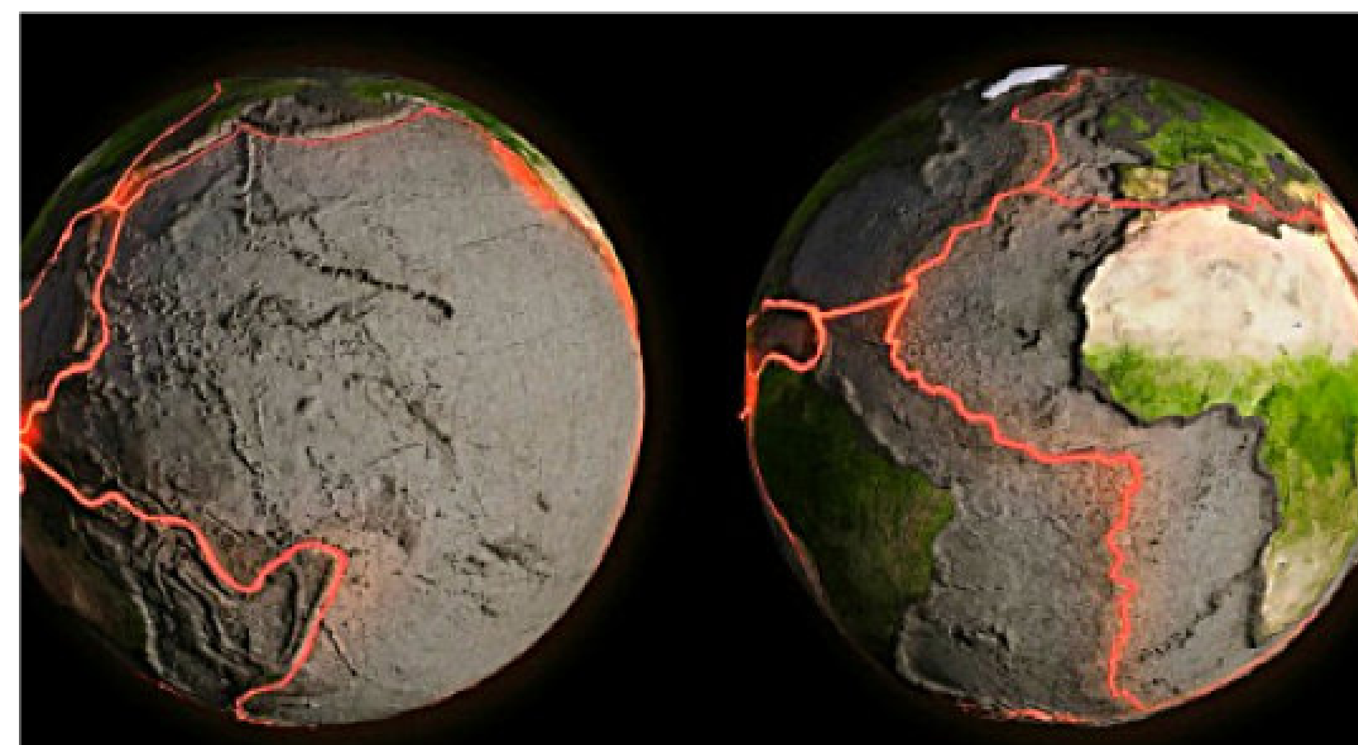
MAYA
REVISTA DE GEOCIENCIAS

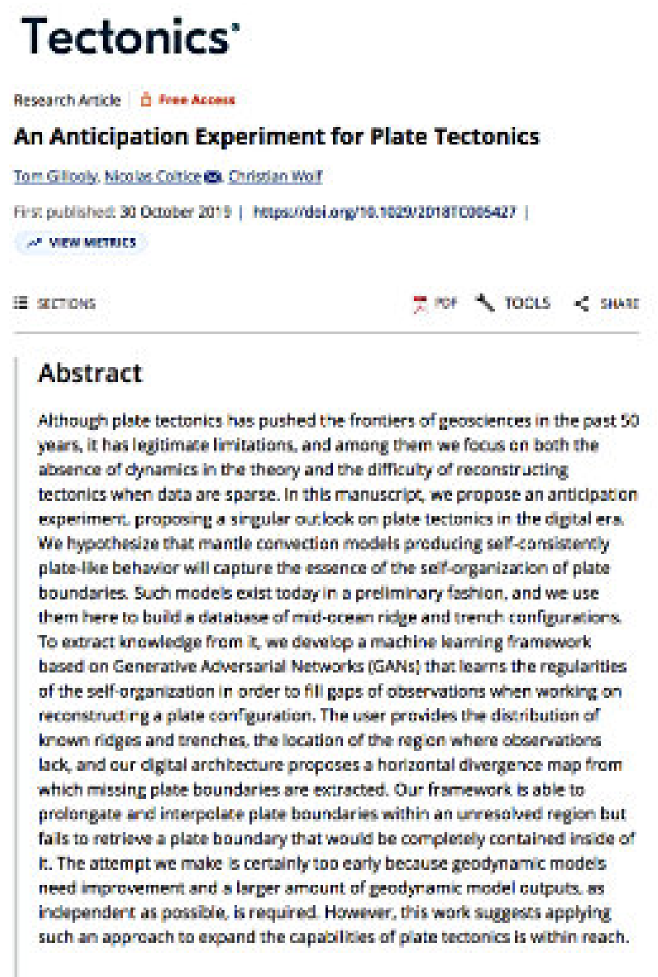
Plate tectonics modelling

Plate tectonics is a highly complex phenomenon that underpins almost every geological process and our understanding of Earth. Increasingly sophisticated computers and statistical approaches, including recent developments in artificial intelligence, allow scientists to build evermore intricate models of the movement of tectonic plates and how their boundaries evolve at different scales of time and space. Which in turn provide a framework to gather further insights on both the history and the future of the planet, the dynamics of various geological processes, location of natural resources, climate and environmental change, and a multitude of other interacting components of the Earth system.

This Collection invites original research on plate tectonics modelling, including multidisciplinary and integrative studies. We will consider contributions to underlying theoretical and statistical aspects, development of new methodological approaches, innovative applications of established techniques, as well as studies showcasing and promoting best research practices.

https://www.nature.com/collections/idaagfhfea





Tectonics

Research Article | Free Access

An Anticipation Experiment for Plate Tectonics

Tom Gilbody, Nicolas Coltice, Christian Wolf

First published: 30 October 2019 | https://doi.org/10.1029/2018TC005427 |

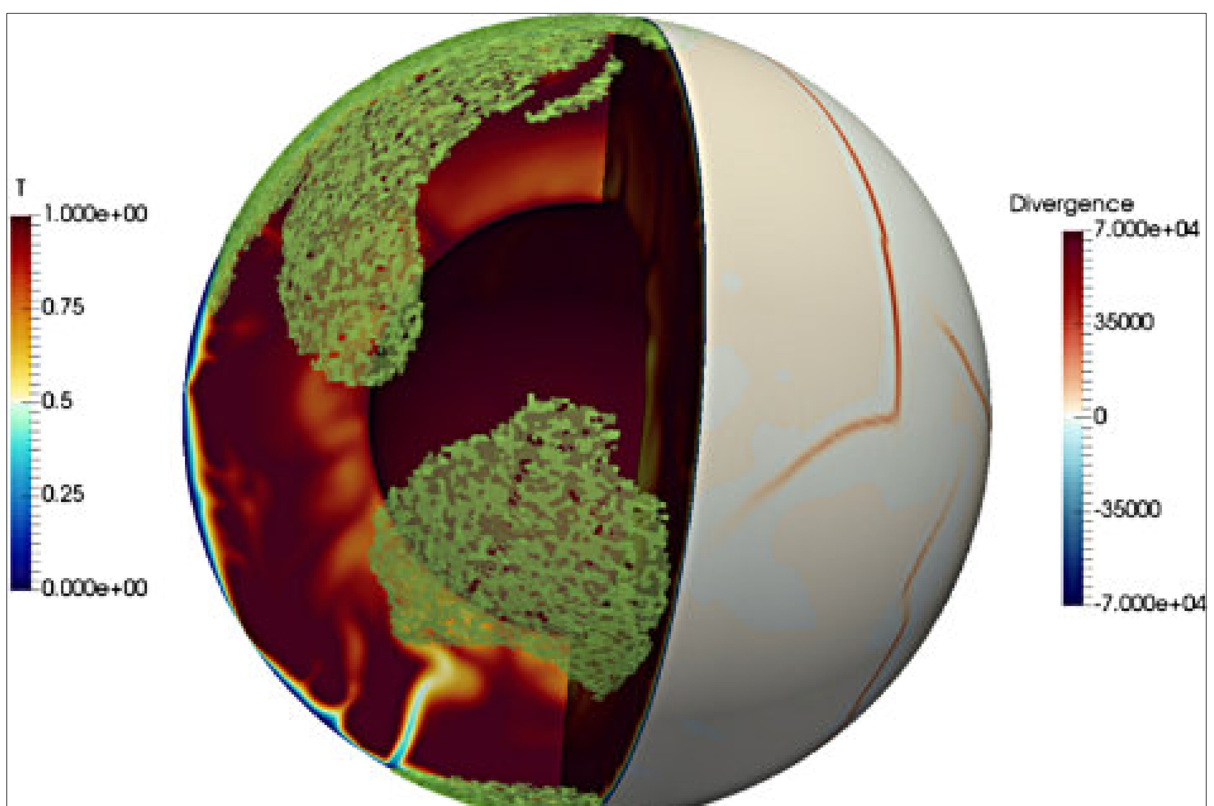
VIEW METRICS

SECTIONS PDF TOOLS SHARE

Abstract

Although plate tectonics has pushed the frontiers of geosciences in the past 50 years, it has legitimate limitations, and among them we focus on both the absence of dynamics in the theory and the difficulty of reconstructing tectonics when data are sparse. In this manuscript, we propose an anticipation experiment, proposing a singular outlook on plate tectonics in the digital era. We hypothesize that mantle convection models producing self-consistently plate-like behavior will capture the essence of the self-organization of plate boundaries. Such models exist today in a preliminary fashion, and we use them here to build a database of mid-ocean ridge and trench configurations. To extract knowledge from it, we develop a machine learning framework based on Generative Adversarial Networks (GANs) that learns the regularities of the self-organization in order to fill gaps of observations when working on reconstructing a plate configuration. The user provides the distribution of known ridges and trenches, the location of the region where observations lack, and our digital architecture proposes a horizontal divergence map from which missing plate boundaries are extracted. Our framework is able to prolongate and interpolate plate boundaries within an unresolved region but fails to retrieve a plate boundary that would be completely contained inside of it. The attempt we make is certainly too early because geodynamic models need improvement and a larger amount of geodynamic model outputs, as independent as possible, is required. However, this work suggests applying such an approach to expand the capabilities of plate tectonics is within reach.

https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018TC005427



MAYA
REVISTA DE GEOCIENCIAS

Collaboration between artificial intelligence and Earth science communities for mutual benefit

10 October, 2024 by Dietmar Müller

A recent analysis concluded that Australia is at risk of losing its world-leading advantage in critical and rare minerals if it doesn't sufficiently leverage artificial intelligence (AI). A large international coalition of Earth scientists and AI researchers is now advocating for stronger bidirectional development and impact between AI and Earth science in a new comment published in Nature Geoscience.

Chen, M., Qian, Z., Boers, N. et al. Collaboration between artificial intelligence and Earth science communities for mutual benefit. Nat. Geosci. 17, 949–952 (2024).

View open pdf here: https://rdcu.be/dWuFp

https://www.nature.com/articles/s41561-024-01550-x.epdf?sharing_token=_3NlWBK0MqFHxxJIynsNN9RgN0jAjWel9jnR3ZoTv0MRAra5992FflrOdNwbTvcyIhZzG3RpE_xeIzSUGRDfwflIWXK0KI9c_jeOO3GaQUpCbo8fWLHdj-FPSuVw7L8kyfoB7xP6uvYHj4snW4D_aQq5iT-GQTTzZrE62bPNrjY%3D

Volume 5, Issue 5, 9 September 2024, 100691

Review

Artificial intelligence for geoscience: Progress, challenges, and perspectives

Tianjie Zhao [1 30], Sheng Wang [2 30], Chaojun Ouyang [3 27 30], Min Chen [4 30], Chenying Liu [5 30], Jin Zhang [6 30], Long Yu [2 30], Fei Wang [7 27 30], Yong Xie [8 30], Jun Li [2 30], Fang Wang [9 27 28], Sabine Grunwald [10], Bryan M. Wong [11], Fan Zhang [12], Zhen Qian [4], Yongjun Xu [7 27], Chengqing Yu [7 27], Wei Han [2], Tao Sun [7], Zezhi Shao [7 27]...Lizhe Wang [2]

Public summary

- What does AI bring to geoscience? AI has been accelerating and deepening our understanding of Earth Systems in an unprecedented way, including the atmosphere, lithosphere, hydrosphere, cryosphere, biosphere, anthroposphere and the interactions between spheres.
- What are the noteworthy challenges of AI in geoscience? As we embrace the huge potential of AI in geoscience, several challenges arise including reliability and interpretability, ethical issues, data security, and high demand and cost.
- What is the future of AI in geoscience? The synergy between traditional principles and modern AI-driven techniques holds immense promise and will shape the trajectory of geoscience in upcoming years.

https://www.sciencedirect.com/science/article/pii/S2666675824001292#undfig1

GRAPHICAL ABSTRACT

MAYA
REVISTA DE GEOCIENCIAS

Here are some scientific papers and research highlights published in 2025 that leverage artificial intelligence and machine learning for the study of plate tectonics and related geophysical processes:

"Inferring Tectonic Plate Rotations From InSAR Time Series" by Liu et al. (**published in Geophysical Research Letters, June 2025**). This research utilizes machine learning techniques to process InSAR (Interferometric Synthetic Aperture Radar) time-series data to infer the angular velocity vectors of tectonic plates, with a focus on the Arabian plate. The associated data and modeling codes are available for use.

"Machine Learning Discovers South American Subduction Zone Hotter than previously Predicted" by Ji et al. (**published in the Journal of Earth Science, June 2025**). This paper highlights how machine learning models can refine predictions about the thermal conditions of major tectonic features, specifically finding the South American subduction zone is hotter than previously understood.

"A machine-learning-based approach using clinopyroxene data to discriminate tectonic settings and magma affinities" by Li et al. (**published in American Mineralogist, July 2025**). This study demonstrates the high accuracy (over 90%) of Support Vector Machines (SVM) and other ML methods in identifying different tectonic settings and magma types based on geochemical data, which was then applied to investigate the breakup of the Rodinia supercontinent.

"Machine Learning and Big Data Mining Reveal Earth's Deep Time Crustal Thickness and Tectonic Evolution: A New Chemical Mohometry Approach" by Zhou et al. (**published in the Journal of Geophysical Research: Solid Earth, May 2025**). This paper presents an ML approach using big data mining of geochemical information to understand the evolution of Earth's ancient crustal thickness and tectonic activity.

"AI could help monitor and predict earthquakes" (**published as a research highlight in AGU Newsroom, July 2025**). This article discusses a Geophysical Research Letter study where scientists trained an explainable AI with a model of subduction zones. The AI identified precursory movements in tectonic plates hours to months before megathrust earthquakes, showing promise for improved monitoring and forecasting.

"A rapid tectonic plate reorganization event driven by changes at subduction locations in a mantle convection model" by Guerrero et al. (**published in Scientific Reports, September 2025**). This paper uses numerical modeling of mantle convection to explore how changes in subduction locations can trigger rapid, global-scale tectonic plate reorganization events.

"Pan-spatial Earth information system: A new methodology for digital Earth" by Chen et al. (**published in The Innovation, March 2025**). This work discusses the use of generative AI to create high-precision digital twin models of Earth's systems, which can efficiently process vast amounts of data and offer insights into historical evolution and future changes in the Earth's environment.