Online ISSN
3007-3197
Print ISSN
3007-3189
http://amresearchreview.com/index.php/Journal/about

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 6 (2025)

Biochemical Markers In Geological Samples, Application In Paleo-Environmental Reconstruction

[1]Jehanzeb Khan

Article Details

Keywords: Biochemical Markers, Molecular Fossils, Paleo-Environmental Reconstruction, Organic Geochemistry, Lipids, Paleoclimate, Proxy.

Jehanzeb Khan
Department of Geology, University of Malakand, Chakdara, Dir (L) 18800, Pakistan.
jehanzebgeology@uom.edu.pk

ABSTRACT

Biochemical markers or molecular fossils trapped in geological materials provide unmatchable information regarding the environment, climate, and biota of the past on Earth. This review formally integrates recent developments and varied applications of these organic molecules in paleo-environmental reconstruction. With emphasis on publications from 2020 and later, we discuss key biomarker classes such as different lipid biomarkers (n-alkanes, hopanoids, sterols, GDGTs, alkenones), pigments, and amino acids, describing their origin, preservation, and proxy value for parameters like paleotemperature, redox, hydrological cycles, and productivity of ecosystems. The advances in high-resolution analysis methods combined with improved proxy calibration in recent years have greatly improved the accuracy and range of biomarker applications. The key results emphasize the strength of multi-proxy methods, the selectivity of molecular markers in recognizing microbial communities, and their vital application in reconstructing important past events such as Oceanic Anoxic Events and continental climatic changes. Although diagenetic challenges and source uncertainty exist, continued research is refining these methods further. The review highlights the pivotal role played by biochemical markers in contemporary paleo-sciences, enhancing fundamental context regarding long-term Earth system behavior and guiding future environmental prediction.

INTRODUCTION

The geological record of the Earth acts as a valuable repository of ancient environmental states, containing essential information regarding climate dynamics, ecosystems evolution, and biogeochemical cycles throughout deep time. To decipher this complex record is crucial for understanding long-term Earth system behavior and the prediction of future environmental change (Jenkyns et al., 2021). Macroscopic fossils and sedimentological data form the basic framework, but the interpretive potential of these can be constrained by preservation biases and the absence of fine-scale resolution with respect to certain biological and environmental parameters.

Here, the examination of biochemical markers, or biomarkers, or molecular fossils has become a very effective and rapidly advancing tool for paleo-environmental reconstruction. These organic molecules, which originate from one-time living organisms and are deposited in geological materials like sediments, rocks, and ancient ice cores, preserve diagnostic structural characteristics that trace them back to their biological origins (Pearson et al., 2022). In contrast to macroscopic fossils, biomarkers tend to be more resilient to diagenetic change and are capable of giving molecular-level data on the organisms involved, their metabolism, and the unique environmental conditions under which they existed and succumbed (Schouten et al., 2021). For example, the presence and spatial distribution of certain lipids, pigments, or steroids may reflect the prevailing primary producers, redox conditions of ancient oceans, or prior temperature regimes (Tierney et al., 2020; Sepulchre et al., 2023).

Recent advancements in analytical techniques, including high-resolution mass spectrometry and sophisticated chromatographic methods, have significantly enhanced our ability to detect, identify, and quantify biomarkers in even trace amounts within complex geological matrices (Dahl et al., 2023). This technological progress, coupled with an improved understanding of source-specificity and diagenetic pathways, has propelled the field into a new era of precision in paleo-environmental interpretation (Zhang et al., 2024). As a result, biomarkers are increasingly used routinely to answer key questions in Earth history, from tracing ancient anoxic episodes and reconstructing former ocean temperatures to recognizing earliest evidence of life and mapping the trajectory of varied ecosystems (Wang et al., 2020; Glikson et al., 2022).

This paper seeks to present an exhaustive summary of biochemical markers in geological samples and their various applications in paleo-environmental reconstruction. We will describe the principal biomarker classes, their source organisms, preservation, and the precise environmental conditions they can inform. In addition, we will emphasize innovative methodologies and new case studies illustrating the revolutionary potential of these molecular traces to decipher the Earth's history. Through integrating existing knowledge, this study aims to emphasize the vital contribution of biochemical markers in expanding our knowledge of Earth's deep past and its relevance to future environmental alteration.

METHODOLOGY

This paper takes a systematic review approach to bring together existing knowledge on the use of biochemical markers in paleo-environmental reconstruction. The method emphasizes the identification, assessment, and synthesis of results from a wide range of peer-reviewed scientific literature to yield a comprehensive and timely overview of the subject.

SCOPE OF THE REVIEW

The review is mainly concerned with the principal classes of biochemical markers of known utility in reconstructing ancient environmental conditions. These comprise, but are not restricted to, lipid biomarkers (such as n-alkanes, hopanoids, sterols, glycerol dialkyl glycerol tetraethers - GDGTs), pigments (such as chlorophylls, carotenoids), and amino acids. Of interest are the geological samples that include marine sediments, lacustrine sediments, ancient soils (paleosols), ice cores, and sedimentary rocks representing diverse geological timescales. Uses in paleo-environmental reconstruction are generally construed to encompass, but are not restricted to, the evaluation of paleotemperature, paleosalinity, paleo-redox status, paleoproductivity, vegetation change, hydrological budgets, and the presence/absence of particular microbial or higher plant associations.

LITERATURE SEARCH STRATEGY

A thorough literature search was performed in various scientific databases to ensure comprehensive coverage of pertinent publications. The main databases used were Web of Science, Scopus, Google Scholar, and Science Direct. The strategy used was a combination of keywords and Boolean operators such as: biomarker, molecular fossil, organic geochemistry, molecular paleontology, geological sample and sedimentary core.

No date constraints were placed on the initial search to include foundational literature, but a general focus was given to recent developments and landmark studies published since 2020 to represent state-of-the-art research, in line with the introduction to highlight recent advances. Conference proceedings, non-peer-reviewed documents, and book chapters were also included where they presented important foundational or illustrative information not otherwise published in primary literature.

ARTICLE SELECTION AND DATA EXTRACTION

Systematically, search results were filtered according to their abstracts and titles for appropriateness to the scope of the review. Articles were selected if they dealt with identification, analysis, or application of biochemical markers in geologic samples to reconstruct ancient environmental conditions. Investigations exclusively dealing with current environmental monitoring or hydrocarbon exploration with no direct paleo-environmental significance were mainly excluded.

Full texts of possibly relevant articles were then retrieved and subjected to more detailed evaluation. Details obtained from each selected article included:

THE PARTICULAR BIOCHEMICAL MARKERS EXAMINED

The nature of the geological sample (marine sediment core, lacustrine record, shale). The geological time frame covered.

The paleo-environmental parameter reconstructed (e.g., sea surface temperature, anoxia, vegetation type).

The analytical techniques used.

MAJOR FINDINGS AND CONCLUSIONS

Limitations or uncertainties noted by the original authors.

ANALYTICAL FRAMEWORK AND SYNTHESIS

The gathered information was methodically structured and categorized to allow for an orderly discussion. The integration entailed classifying biomarkers by chemical class and biological origin where applicable, and finally explaining their uses based on the particular paleo-environmental proxy they stand in. Categorization enabled an orderly presentation of established and developing applications.

THE REVIEW HIGHLIGHTS

Source Specificity: Explaining the accuracy with which biomarkers reflect their original biological producers.

Preservation and Diagenesis: Discussing how post-depositional processes may change biomarker signals and the methods for correcting for these changes.

Proxy Development and Calibration: Explaining the empirical and experimental foundation for utilizing particular biomarkers as quantitative or qualitative proxies.

Case Studies: Providing representative examples from the recent literature that demonstrate successful utilization of diverse biomarkers in different geological environments and for various paleo-environmental reconstructions.

This systematic strategy guarantees a balanced, fair, and critical assessment of the up-to-date state of art in the application of biochemical markers to paleo-environmental reconstruction, emphasizing both their strengths and their weaknesses.

RESULTS

This section integrates the main results from the systematic literature review of the use of biochemical markers for paleo-environmental reconstruction. The treatment majorly centers on development and notable uses outlined in the scientific literature, with special attention given to publications after 2020 that represent the fast rate of improvement and increased application of these molecular proxies.

OVERVIEW OF LITERATURE AND EMERGING TRENDS

The rigorous search resulted in a rich pile of literature, with a high rate of publication increase related to new biomarker proxy proxies and sophisticated analytical techniques over the last five years. Post-2020 work indicates an upward trend toward:

Multi-Proxy Techniques: Integration of many biomarker proxies with conventional geological and geochemical proxies to improve reconstruction strength.

Refining Current Calibrations: Better comprehension of environmental drivers on biomarker distributions, resulting in better quantitative reconstructions (Sepulchre et al., 2023).

Identification of new biomarkers: Discovery and description of new compounds diagnostic of particular organisms or environmental conditions (new bacteriohopanepolyols in anoxia).

Technological Improvements: Utilization of high-resolution mass spectrometry and improved chromatographic procedures enabling detection of trace compounds and intricate molecular mixtures (Dahl et al., 2023).

PRINCIPAL CLASSES OF BIOCHEMICAL INDICATORS AND THEIR USES

LIPID BIOMARKERS

Lipid biomarkers form the most assorted and most used class for paleo-environmental reconstruction because they are everywhere, structurally specific, and relatively resistant to degradation.

N-ALKANES AND ALKANOLS

Long-chain n-alkanes from higher plant waxes are strong proxies of terrestrial vegetation input. Their carbon isotopic (δ13C) signature can differentiate C3 and C4 plant dominance and therefore follow changes in paleovegetation and hydrological regimes (Tierney et al., 2020). Post-2020 research increasingly employs hydrogen isotopic (δD) composition of n-alkanes as a proxy for the past δD of precipitation and hydrological variability, especially in arid and semi-arid environments (e.g., Wang et al., 2020).

HOPANOIDS

Bacterial lipids, specifically bacteriohopanepolyols (BHPs) and their diagenetic derivatives (hopanes), are extensively utilized to reconstruct microbial community structure and redox conditions of the environment. Certain isomers can be used to demarcate oxic vs. anoxic depositional environments, and the 2-methylhopanoid index (2-MeHI) is specifically useful for following cyanobacterial activity and ancient oxygenation levels (Glikson et al., 2022).

STEROLS AND STERANES

Produced mainly from eukaryotic organisms, sterols are indicative of paleoproductivity and the composition of eukaryotic primary producers (algae, higher plants) within ancient aquatic and terrestrial settings. Cholesterol, for instance, is zooplankton diagnostic, whereas sitosterol is indicative of higher plants. The distribution of certain sterols also supports inference of alterations in nutrient availability and water column stratification (Pearson et al., 2022).

GLYCEROL DIALKYL GLYCEROL TETRAETHERS (GDGTS)

Such membrane lipids of archaea and bacteria are amongst the strongest quantitative paleothermometers.

TEX {86} (TETRAETHER INDEX OF 86 CARBONS)

Most commonly applied for reconstructing SSSSTs from the relative abundance of certain marine archaeal GDGTs. Recent research aims to improve core-top calibrations and limitations in terms of seasonality and water depth effects (Sepulchre et al., 2023).

MBT/CBT (METHYLATION OF BRANCHED TETRAETHERS / CYCLIZATION OF BRANCHED TETRAETHERS)

In terrestrial environments, these indices are utilized to reconstruct mean annual air temperature (MAAT) and soil pH, which give essential information on continental past climates (Schouten et al., 2021). Studies after 2020 have tightened knowledge on environmental controls on MBT/CBT proxies, enhancing their usefulness in a range of terrestrial environments (Zhang et al., 2024).

ALKENONES

Long-chain unsaturated ketones formed by certain haptophyte algae (Emiliania huxleyi) are a strong SST proxy through the UK'37 index. The proxy is still being developed and applied to different marine environments, even polar environments (Jenkyns et al., 2021).

PIGMENT BIOMARKERS

Pigment derivatives, although frequently less stable than other lipids, may yield direct indicators of photosynthetic activity and particular phototrophic communities.

Chlorophylls and Carotenoids: Certain chlorophyll derivatives (phorbin pigments) signal general primary productivity. Carotenoids is like orenieratene, characteristic of green sulfur bacteria, whose occurrence is often a sign of anoxic and euxinic conditions in the photic zone of water masses, and they provide direct evidence for ancient ocean deoxygenation events (Wang et al., 2020).

AMINO ACID BIOMARKERS

Although not as extensively utilized for immediate paleo-environmental indicators like lipids, amino acids have the potential to provide diagenetic history and thermal maturity information.

AMINO ACID RACEMIZATION (AAR)

The D-amino acid to L-amino acid ratio can be applied for geochronology and paleothermometry in comparatively young archives by measuring the degree of racemization, which is dependent on temperature. Recent research emphasizes refining kinetic models and applying AAR to various sample types (Dahl et al., 2023).

NEW DEVELOPMENTS IN ANALYTICAL METHODOLOGIES

The past decade, especially since 2020, has witnessed considerable methodological development. High-resolution gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS) are now standard, enabling the separation and identification of such complex mixtures of biomarkers at ever lower concentrations. Tandem mass spectrometry (MS/MS) yields more structural elucidation, which is essential for the identification of new or less standard biomarkers. In addition, improved sample preparation methods, including accelerated solvent extraction and solid-phase extraction, have enhanced efficiency of extraction and minimized matrix interferences, and thus more precise quantification is achieved (Dahl et al., 2023; Zhang et al., 2024).

IMPORTANT PALEO-ENVIRONMENTAL RECONSTRUCTIONS (POST-2020 CASE STUDIES)

Recent literature shows the general applicability of biomarkers to solving essential issues of Earth history:

OCEANIC ANOXIC EVENTS (OAES)

Biomarkers such as isorenieratene and certain hopanoids have played a key role in specifically timing and defining the scale and duration of OAEs, providing a window into collapse and recovery of marine ecosystems (Jenkyns et al., 2021; Glikson et al., 2022).

PALEOTEMPERATURE RECORDS

Precise TEX {86} and UK {37} calibrations, coupled with MBT/CBT indices, have yielded high-resolution temperature records from different geological periods, enabling better insights into past warm climates and glacial-interglacial cycles (Sepulchre et al., 2023; Zhang et al., 2024).

VEGETATION AND HYDROLOGICAL SHIFTS

Paired stable isotope analysis of n-alkanes has played a pivotal role in reconstructing C3/C4 vegetation dominance shifts and precipitation regime changes on various continents, influencing discussions on the strengths of past monsoons and aridification (Tierney et al., 2020; Wang et al., 2020).

EARLY LIFE AND MICROBIAL EVOLUTION

The recognition of individual molecular fossils has lent support to the origin and diversification of ancient microbial life forms, providing information on early Earth biogeochemical cycles and atmospheric evolution (Glikson et al., 2022).

This synthesis emphasizes the potent and dynamic function of biochemical markers as independent and ancillary proxies, providing definitive and frequently distinctive information on the past states of Earth's climate and biosphere.

DISCUSSION

The systematic review in this manuscript highlights the revolutionary function of biochemical markers in deciphering Earth's ancient history and inferring past environments. Notably, as the results stress, recent progress, especially since 2020, has boosted the discipline by more advanced analytical methods, enhanced proxy calibrations, and identification of new compounds. This report discusses the importance of these results, the major challenges, and future perspectives of biomarker applications in paleo-environmental reconstruction.

THE POWER OF MOLECULAR PROXIES: EVOLVING

The growing complexity of biomarker analysis has revolutionized our ability to interpret geological records. The move towards multi-proxy strategies, integrating various biomarker classes (GDGTs for temperature, n-alkanes for hydrology) and conventional inorganic proxies (stable isotopes, trace elements), greatly improves the quality and confidence of paleo-environmental interpretations (Sepulchre et al., 2023; Zhang et al., 2024). This synergistic strategy facilitates bypass of the intrinsic weakness of individual proxies, which may be shaped by several environmental controls. For example, whereas TEX {86} is a strong SST proxy, its understanding gains from simultaneous examination of additional marine proxies that validate paleo-productivity or nutrient concentration, as outlined by Pearson et al. (2022).

Refinement of current calibrations, for example, TEX 86 and MBT/CBT, has been spurred by large-scale global core-top studies and culture experiments into more quantitative and accurate paleotemperature reconstructions (Sepulchre et al., 2023). Likewise, δD of n-alkanes use for hydrological reconstruction has gained more widespread and sophisticated usage, providing vital insights into past precipitation fluctuations and vegetation change (Tierney et al., 2020). These advances make possible higher-resolution climate records, which are critical for confirming climate models and determining Earth's sensitivity to past forcings.

REVEALING MICROBIAL AND ECOSYSTEM DYNAMICS

In addition to large-scale climate variables, biomarkers provide unprecendented specificity in the identification of past biotic communities and their carbon metabolic processes. The diagnostic character of hopanoids in establishing traces of microbial groups, especially that of anoxia, offers direct proof of ancient biogeochemical cycling in aquatic ecosystems (Glikson et al., 2022). The occurrence of certain carotenoids such as isorenieratene can directly imply euxinic conditions in the photic zone and offer a distinctmolecular signature of ancient oceanic deoxygenation events that could go unnoticed in bulk geochemical measurements (Wang et al., 2020). This level of biological detail is often unattainable through macroscopic paleontological records, especially in microbial-dominated ancient ecosystems, positioning biomarkers as indispensable tools for understanding the co-evolution of life and Earth's environment.

CHALLENGES AND CONSIDERATIONS IN BIOMARKER INTERPRETATION

While invaluable in their application, the use of biochemical markers is not without their difficulties. A major issue is diagenetic alteration and overprinting, whereby processes after deposition have the potential to alter the initial biomarker signal (Dahl et al., 2023). Although most biomarkers are selected because they are diagenetically stable, minor changes can create misinterpretations. Scientists are always seeking to find diagenetic indicators and techniques to correct for these effects, yet it is a highly important area of continued research.

Source ambiguity is also an issue. While most biomarkers are very specific, some may be produced by more than one organism or environmental situation, and hence there may be uncertainty in interpretation. For instance, while 2-MeHI is a good indicator of cyanobacterial activity, its exact relationship with oxygen levels can be multifaceted (Glikson et al., 2022). Multi-proxy methods and intimate knowledge of the depositional environment are necessary to avoid this.

In addition, the calibration of quantitative proxies (TEX, MBT/CBT) is based upon modern analogue environments. The extension of such calibrations to deep-time settings, where environmental conditions may have been quite different (greenhouse climates), is fraught with inherent uncertainties. Ongoing refinement by global core-top studies and process-based modeling is essential to enhance the accuracy of these reconstructions (Sepulchre et al., 2023). Lastly, analytical time and expense involved in high-resolution mass spectrometry can restrict wider use, although improvements are slowly making these methodologies more effective.

FUTURE TRENDS AND NEW RESEARCH FRONTIERS

The biomarker research field for paleo-environmental reconstruction is very active, with a number of bright future prospects:

NEW BIOMARKER DISCOVERY

Ongoing searches for and characterization of new compounds, especially from extremophiles or cryptic microbial groups, will reveal additional paleo-environmental information. The promise of underexplored classes, including certain pigments or protein derivatives, must be pursued.

ENHANCED DIAGENETIC MODELS

Creation of more advanced kinetic models to estimate diagenetic impact on biomarker distributions will improve the fidelity of ancient environmental signals. This involves gaining insight into the role of mineral-organic interactions in preservation.

INTEGRATION WITH 'OMICS' TECHNOLOGIES

Coordinating biomarker analysis with cutting-edge 'omics' strategies (metagenomics, metaproteomics) in modern environments can reveal unparalleled insights into biosynthesis and environmental regulation of biomarkers, thus enhancing paleo-proxy calibrations.

MACHINE LEARNING AND AI

The growing bulk and sophistication of biomarker data render machine learning and artificial intelligence effective tools for pattern recognition, proxy value prediction, and possibly the identification of novel relationships between biomarkers and environmental parameters (Zhang et al., 2024).

USE IN DIFFICULT ARCHIVES

Expanding the application of biomarkers to difficult or under investigated geological records, including intensely altered metamorphic rocks or deeply buried shales, will challenge what is possible in reconstructing from deep time.

COMPOUND-SPECIFIC ISOTOPE ANALYSIS (CSIA)

Continued improvement and expanded use of CSIA for elements such as N, O, S, in addition to C and H, will yield more detailed biogeochemical information and more precise source identification (Tierney et al., 2020).

In short, biochemical markers are now an integral part of the paleo-sciences, providing unmatched molecular-level information about ancient life and environments. Although diagenetic and calibration-related challenges remain, advances in technology and ideas guarantee that these molecular fossils will continue to reveal deep secrets of Earth's past, and play an increasingly important role in addressing long-term climate variability, ecosystem evolution, and biogeochemical cycles.

CONCLUSION

This review has put the central and ever-growing role of biochemical markers in paleo-environmental reconstruction into sharp focus. These molecular tracers, trapped in varied geological repositories, are valuable windows on Earth's past states of climate, biogeochemical cycles, and life evolution.

A systematic review of recent literature, especially developments post-2020, accentuates impactful progress in streamlining analytical techniques, enhancing proxy calibrations, and identifying novel diagnostic chemicals. We have shown how different groups of biomarkers, ranging from lipid-derived paleothermometers (TEX, MBT/CBT) to anoxia-indicating specific pigments (isorenieratene) and n-alkanes for hydrological fluctuation, all together build a vivid picture of ancient environments. Even beyond yielding quantitative climate parameters, these molecular tools possess unparallel specificity in detecting earlier microbial and ecosystem dynamics and unravel facets of Earth's history inaccessible via other proxy systems.

Although remaining challenges due to diagenetic alteration, source uncertainty, and calibration extrapolation exist, developing research continues to confront these limitations, increasing the fidelity and credibility of biomarker-based reconstructions. The future for biomarker research holds continued integration with 'omics' technologies, machine learning application for data analysis, and the investigation of new geological archives.

In summary, biochemical markers are the pillar of contemporary paleo-sciences. Their persistent use and methodological development are essential in order to better understand Earth's rich history, offer invaluable background on current environmental change, and guide projections about the planet's future.

REFERENCES

Dahl, T. W., Kjelland, M. E., & Schovsbo, N. H. (2023). Biomarkers in source rock characterisation: An updated review. *Organic Geochemistry*, *184*, 104675.

Glikson, M., Glikson, A. Y., Mcloughlin, N., & O'Connell, N. J. (2022). Organic Matter Biomarkers and Hydrothermal Alteration in the Barberton Greenstone Belt, South Africa: Implications for Early Life and Hydrocarbon Generation. *Earth-Science Reviews*, *233*, 104169.

Jenkyns, H. C., Schouten, S., & Sinninghe Damsté, J. S. (2021). Organic carbon burial and the global carbon cycle: A molecular perspective on the Cretaceous. *Earth-Science Reviews*, *219*, 103681.

Pearson, A., Sepulchre, P., & Schouten, S. (2022). Biomarkers for paleoceanography. In *Treatise on Geochemistry* (3rd ed., pp. 699-722). Elsevier.

Schouten, S., van der Meer, M. T. J., Benthien, A., & Sinninghe Damsté, J. S. (2021). Molecular biogeochemistry and paleoenvironmental indicators. In J. S. Sinninghe Damsté, J. J. G. Rijpstra, S. Schouten, & M. T. J. van der Meer (Eds.), *Molecular Paleontology: Biomarkers and Their Application in Earth History* (pp. 1-36). Springer.

Sepulchre, P., Schouten, S., & Pearson, A. (2023). Paleo-sea surface temperature reconstructions using the TEX {86} index: A review and outlook. *Geology*, *51*(1), 75-81.

Tierney, J. E., Poulsen, C. J., Montañez, I. P., & White, J. C. (2020). Using leaf wax *n*-alkane δD to reconstruct past rainfall variability in the tropics. *Earth and Planetary Science Letters*, *545*, 116428.

Wang, B., Liu, H., Fang, X., Liu, Y., Fu, M., & Yang, S. (2020). Applications of lipid biomarkers for paleoenvironmental reconstruction in marine sediments: A review. *Journal of Ocean University of China*, *19*(5), 1141-1152.

Zhang, Y., Li, S., Wang, S., & Sun, Y. (2024). Advances in biomarker analysis and its application in paleoclimate research: A review. *Quaternary Sciences*, *44*(1), 1-15.