

Investigating the application of LLMs to invertebrate palaeontology through the development of automated taxonomy assistants for brachiopod identification

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Abstract

Taxonomic identification is a central practice in palaeontology, underpinning biostratigraphic correlations, palaeobiogeographic reconstructions, and analyses of macroevolutionary patterns. Despite its importance, taxonomy depends on a limited number of specialists and on the synthesis of extensive descriptive literature that is often difficult to access. Recent developments in artificial intelligence provide potential tools to support taxonomic work and improve accessibility and efficiency in fossil identification. Most automated approaches have so far relied on deep learning models trained on photographic datasets of fossil specimens. While effective for some microfossil groups, these systems face substantial limitations when applied to macrofossils, which are often incompletely preserved, morphologically complex, and poorly suited to standardized imaging workflows.

*Because palaeontological taxonomy is fundamentally text-based—relying on diagnoses, descriptions, and comparative remarks published in the literature—Large Language Models (LLMs) offer an alternative framework for automated assistance. Here we explore the application of LLM-augmented taxonomy systems (LATS) to invertebrate fossil identification through the development of a prototype system for brachiopods. The system is trained on genus-level diagnoses extracted from the *Treatise on Invertebrate Paleontology, Part H: Brachiopoda (Revised)*, one of the most comprehensive and authoritative compilations of fossil invertebrate taxonomy. Strategies were implemented to address the brevity of diagnoses, including integration with descriptions of higher-rank taxa and adjustable retrieval knowledge basis.*

Preliminary testing indicates that the system reliably provides plausible candidate matches and handles complex morphological terminology effectively. LATS thus represent a promising approach for developing automated assistants in macrofossil taxonomy, with potential future integration of expanded textual databases and image-based analyses.

Introduction

Palaeontology, the study of the fossilised remains of past organisms, relies primarily on the practice of attributing fossils to a hierarchical system of taxonomic categories. The taxonomic identification of fossils collected in the field, mostly relying on their morphological characters, underpins biostratigraphic correlations, biozonation of stratigraphic successions, palaeobiogeographic reconstructions, calculation of rates of extinction and origination, etc.

Despite its central role, taxonomy remains heavily dependent on a shrinking pool of specialists and on the synthesis of extensive descriptive literature, often available only under paywall and/or in paper copies in institutions around the globe. Recent advances in artificial intelligence might cope with these problems, providing assistance and guidance to early career researchers in fossil identification and increasing the accessibility, standardization and efficiency of taxonomic practise (Yu et al., 2025; Stephenson et al., 2025, 2026).

To date, most automated approaches have focused on deep learning models trained with databases of images of fossil specimens identified by experts. These systems have for now mostly been developed for small sets of microfossil taxa, such as foraminifers, graptolites and palynomorphs (e.g., Ranaweera et al., 2009; Mander et al., 2013; Romero et al., 2020; Niu et al., 2024), benefiting from standardized specimen preparation and large volumes of complete specimens available to be illustrated in 2D uniform photographs—conditions rarely met by macrofossils. Macrofossils are commonly incompletely preserved, embedded within heterogeneous matrices, and affected by taphonomic processes that obscure diagnostic characters. For groups defined by complex three-dimensional morphology and fine-scale features, including microstructure and internal anatomical characters (e.g., brachiopods, corals, vertebrates), image-based automation would require extensive three-dimensional scans, high-resolution imagery, and large curated datasets, rendering this strategy impractical for routine research. Beyond data volume, image-based systems face a fundamental lack of taxonomic authority: photographic datasets used to train deep learning models need to be examined by human experts in order for the specimens to be identified. This not only represents a prohibitive investment of specialist time and effort but also means that the system in the end reflect only the taxonomic opinion of the expert identifying the fossils. The development of new approaches, such as unbiased unsupervised machine learning systems (e.g., Hartmann et al., 2026), could partially alleviate these limitations by detecting patterns in high-dimensional morphological space and reducing dependence on prior taxonomic assignments. However, the translation of these clusters into taxa meaningful to palaeontology and biology still requires expert interpretation, and should be encased into the rules of the Linnaean taxonomic system.

Actually, palaeontological taxonomy is fundamentally text-based. Diagnoses, descriptions, and comparative remarks in monographs, books and papers constitute the authoritative record of taxa, encoding the approach and logic by which identifications are performed. Published, widely-distributed texts providing the diagnoses and descriptions of taxa based on name-bearing type specimens constitute the formal nomenclatural acts recognised by the International Commissions on Zoological (ICZN, 1999) and the International Commission on Botanical Nomenclature (Turland et al., 2025), and thus constitute the highest possible authority.

Among artificial intelligence systems, Large Language Models (LLMs) are thus well suited to operate within taxonomy. Stephenson et al. (2025, 2026) applied LLMs to paleo-palynological taxonomy and illustrated how LLM-augmented taxonomy system (LATS) are able to navigate through extensive databases of genera descriptions (>4500 genera are included in the palynomorph database of Stephenson et al., 2026, derivative from the catalogue of Jansonius and Hills, 1967),

interpret morphological terminology and recognise similarity between a user prompt description of a specimen and genera diagnoses in the database, providing a list of reasonable matches.

Here we investigate the potential of applying LLMs to invertebrate fossil taxonomy, describing and discussing the preparation and functioning of a LATS for fossil brachiopod identification. The system is trained on genus-level diagnoses from the *Treatise of Invertebrate Paleontology, Part H: Brachiopoda, Revised* (Williams et al., 1997, 2000, 2002, 2006, 2007). The *Treatise on Invertebrate Paleontology* comprises 55 volumes containing an almost complete list of all described genera of invertebrate fossils (up to publication), with diagnoses for each genus emended by the more prominent experts of each group (Histon in Selden et al., 2025). The *Treatise* thus provides the most complete, free access and authoritative catalogue of fossil invertebrate genera, though conspicuous challenges in using it as a database for the development of a LATS should be taken into consideration.

Materials and Methods

The Treatise of Invertebrate Paleontology

The *Treatise of Invertebrate Paleontology* is a series of 55 volumes co-published by The University of Kansas Paleontological Institute and the Geological Society of America from 1953 to 2000, by the University of Kansas Paleontological Institute only since 2008 (Selden in Selden et al., 2025). The *Treatise* is subdivided into a number of sections (A to W), each dedicated to a specific phylum or major group of fossils and edited by the major leading experts on the systematics and taxonomy of that fossil category. The *Treatise* volumes do not provide the original diagnoses of the genera extracted from the literature; instead, they provide synthetic emended diagnoses containing just the essential information to allow the discrimination of each genus from the allied ones.

Even though the *Treatise* volumes do not report original diagnoses of taxa, they are widely considered as authoritative by the paleontological community, as each section has been compiled by the joint effort of the community of expert of each group of fossil, supervised by a leading expert in the field (e.g., Harper in Selden et al., 2025). Before the preparation of each part, morphological terminology and the classification scheme adopted for the group was discussed among all the community, thus providing standards which have usually persisted in each taxonomy community for decades. During preparation of the *Treatise* volumes, many genera are re-considered and re-examined and thus their diagnoses emended, and synonyms described from different regions recognised; this has proven particularly useful for invertebrate fossil taxonomy, especially in the case of genera poorly described in the 18th and 19th centuries. In the case of most fossil groups, the *Treatise of Invertebrate Paleontology* is the only comprehensive compilation of described genera and is thus vital to the work of taxonomists, which would have otherwise to check hundreds of descriptions scattered in the systematic literature, most likely overlooking genera described in contributions not available in their institution libraries or online (Histon in Selden et al., 2025). Physical copies of the *Treatise* volumes are available in most institutions, and the .pdfs are mostly freely accessible online.

Despite the undeniable contribution of the *Treatise* system to the stability and efficiency of invertebrate fossil taxonomy, some issues regard the difficulty of updating the volumes: the preparation of each section of the *Treatise* takes a huge effort by tens of experts distributed around the globe, and usually more than a decade (e.g., 22 years from conception to publication of the last volume of *Brachiopod Revised Treatise*, Harper in Selden et al., 2025). Many sections were not

updated after their first publication in the '50s– '60s, meaning that, despite being still useful, they do not contain a full record of the genera in the fossil group, and are based on outdated stratigraphic information and classifications. Though not one of the most quickly evolving fields of science, invertebrate fossil taxonomy moves on steadily with the definition of many new taxa each year: as an example, the Revised volume of Part H Brachiopoda (Williams et al., 1999, 2000, 2002, 2006, 2007) contains 4192 genera, whereas the first version (Williams et al., 1965) has 1700 only (Harper in Seldon et al., 2025).

Updating the Treatise volumes is becoming lately even more challenging given the global tendency of reducing amount of taxonomy experts, limited generational change in taxonomy, and increasing duty pressure on academics limiting their capability of engaging in such a challenging task. Efforts such as the publications of individual revised Treatise chapters when available (Treatise Online; Histon in Seldon et al., 2025) and the preparation of an online, freely accessible database of Treatise genera (Ogg, 2025) are trying to cope with these problems.

To develop a sample LATS from the Treatise, the decision was taken to develop an assistant for brachiopod identification based on the volumes of the Treatise of Invertebrate Paleontology, Part H: Brachiopoda, Revised (Williams et al., 1997, 2000, 2002, 2006, 2007). The Revised version of Part H of the Treatise constitutes one of the most recently updated and complete parts, providing a complete record of brachiopod taxonomy up to 2007, and reflecting the opinions of all the brachiopod expert community of last and current generations (Harper in Seldon et al., 2025).

Approach and principles

In approaching the preparation of the Brachiopod Treatise LATS, the three principles followed by Stephenson et al. (2026) in the preparation of the paleo-palynology LATS based on the Jansonius and Hills catalogue (JH) were followed: 1) principle of inclusion, meaning the system is designed to include, rather than exclude candidate genera, providing the most possible complete list of candidates to the user; 2) principle of assistance, meaning that the LATS is designed to assist the taxonomist in taxonomic identification, giving a number of possible candidates and a clear rationale of morphological similarity between the prompt and candidate genera, but not to substitute itself to the human user; 3) principle of non-intervention, meaning that no or minimal intervention and supposed improvement to the quality of the genera diagnoses is made by the team, in order to preserve the authoritative record of the data deriving from the Treatise.

The preparation of the Treatise Brachiopod LATS provided new challenges with respect to the JH LATS (Stephenson 2026). One obvious application of the principle of inclusion to the preparation of the Treatise data was the decision to avoid the use of the stratigraphic range as a criterion to exclude potential candidates. Even if homeomorphs are common among brachiopods, given their limited genetic pools (Cohen, 2007), the common practise among taxonomists to take into consideration only genera originally defined stratigraphically and geographically close to the investigated localities might result in overestimation of bioprovincialism and artificial extinction events at the boundary of stratigraphic intervals. The information on the stratigraphic distribution of genera, always included in the Treatise for each genus, has been thus included in the database and made available to the user for consideration, but does not influence the inclusion or exclusion of the genus from the candidate list provided by the LLM.

Another issue regards the nature of the genera diagnoses in the Treatise. While the JH database provides complete descriptions of palynomorph genera derived verbatim from the palynology

literature, the Treatise contains emended synthetic diagnoses including only the information necessary for discriminating the genera from allied ones. Characters which are common to group of allied genera are described in the descriptions of taxa of family, order and class rank. In order to include in the database used by the LATS the most complete description of the characters of each genus, the decision was made to also extract the family, order and class rank descriptions, and to merge these to the descriptions of each genus contained within them. This would make possible the comparison of complete descriptions of fossil specimens inserted as prompts by the users and the set of characters for each genus in the LATS database (Fig. 1).

The merging of information at different taxonomic ranks implies that conflict would arise between lower and higher rank descriptions: in the example reported in Fig. 1, the description obtained in the LATS database from merging genus + family level descriptions of *Cyrtia* contains conflicting information on the characters of the delthyrium at family ('delthyrial plates and stegidial plates lacking') and superfamily level ('delthyrium occluded by deltidium, delthyrial plate, or stegidial plates'). In case of conflicting information, the LATS is trained to consider the information from the lowest taxonomic rank, in this case, the Family.

<p>Superfamily CYRTIOIDEA Frederiks, 1924</p> <p><small>[nom. conserv. JOHNSON, GOURDINNEC, & HOU in CARTER & others, 1994, p. 330, pro superfamily Cyrtiacea PITRAT, 1965, p. 668, nom. transl. ex Cyrtiinae FREDERIKS, 1924, p. 312]</small></p> <p>Commonly with fold and sulcus; surface smooth or plicate; microornament of non-spinose capillae crossed by variably nodose growth lines; delthyrium occluded by deltidium, delthyrial plate, or stegidial plates; dental plates present; crural plates variably developed. <i>upper Upper Ordovician–Lower Devonian (Emsian).</i></p> <p>Family CYRTIIDAE Frederiks, 1924</p> <p><small>[nom. transl. IVANOVA, 1959, p. 55, ex Cyrtiinae FREDERIKS, 1924, p. 312] [=Eospiriferinae SCHUCHERT, 1929, p. 20]</small></p> <p>Delthyrial plate and stegidial plates lacking; crural plates commonly well developed. <i>upper Upper Ordovician–Lower Devonian (Emsian).</i></p> <p>Subfamily CYRTIINAE Frederiks, 1924</p> <p><small>[Cyrtiinae FREDERIKS, 1924, p. 312]</small></p> <p>Ventribiconvex; ventral valve hemipyramidal, with catacline or procline interarea and narrowly elongate delthyrium; deltidium with medial foramen; ctenophoridium absent. <i>Silurian (upper Llandovery–Ludlow).</i></p> <p><i>Cyrtia</i> DALMAN, 1828, p. 97 [*<i>Anomites exprorectus</i> WÄHLENBERG, 1821, p. 64; SD DAVISON, 1853, p. 83]. Nontransverse to transverse; lacking plications. <i>Silurian (upper Llandovery–lower Ludlow): cosmopolitan.</i>—FIG. 1105, 1A–d. *<i>C. exprorecta</i> (WÄHLENBERG), upper Llandovery, Gotland; posterior, anterior, side, and ventral views, ×3 (Boucot, 1963a).</p>	<p>Genus diagnosis in LATS database (genus + family rank descriptions option):</p> <p><i>Cyrtia</i>: Nontransverse to transverse; lacking plications. Ventribiconvex; ventral valve hemipyramidal, with catacline or procline interarea and narrowly elongate delthyrium; deltidium with medial foramen; ctenophoridium absent. Delthyrial plate and stegidial plates lacking; crural plates commonly well developed. Commonly with fold and sulcus; surface smooth or plicate; microornament of nonspinose capillae crossed by variably nodose growth lines; delthyrium occluded by deltidium, delthyrial plate, or stegidial plates; dental plates present; crural plates variably developed.</p>
Superfamily description	
Family description	
Subfamily description	
Emended genus diagnosis	

Fig. 1. Hierarchical structure of taxonomic descriptions in the Treatise and resulting genus description in the database. Information on delthyrium region is underlined in each taxonomic rank level.

On the other hand, the fact that the Brachiopod Treatise contains only genera diagnoses emended by a team of experts under the editorial guidance of A. Williams and C.H.C. Brunton over a short period of time results in uniform use of morphological terminology and formatting of diagnoses. LLM training thus did not require the creation of “question-and-answers pairs” as in the case of the JH system (Stephenson et al., 2026), but simply the use as learning material of the Glossary on

Brachiopod Terminology by Williams and Brunton (1997), which resulted in a satisfactory increase of the LATS semantic understanding.

Preparation of the LATS

Data extraction

The volumes of the Treatise of Invertebrate Paleontology, Part H Brachiopoda, Revised (Williams et al., 1997, 2000, 2002, 2006, 2007), are available in high-quality .pdf files, thus extraction of the data from the volumes was executed almost without problems of text machine recognition. Genera diagnoses, and information about their authorship, classification, synonyms, stratigraphic range, was extracted by the team coordinated by Prof. James Ogg and Prof. Aaron Ault by the Earth History Visualization team of undergraduate computer engineers at Purdue University in the context of the project the creation of an online, publicly accessible Treatise genera database (Ogg, 2025). Permission to use these data for the preparation of an LLM for brachiopod taxonomy was provided by the Purdue University team and the current Treatise editor, Bruce S. Lieberman at The Paleontological Institute at the University of Kansas.

Given the necessity to merge in the database also descriptions of taxa of the family, order and class rank, these were extracted by the team led by JW at the Zhejiang laboratory, Hangzhou, and revised by APC. As descriptions of class and subphyla contain information not useful for morphological fossil identification (physiology, morphology of soft parts) these parts of the descriptions were removed and resulting shorter descriptions revised by a team of expert collaborators.

Model construction

The LATS operates as in the case of the JH system prepared for paleo-palynology by Stephenson et al. (2026). The LATS works through three steps (Fig. 2).

- 1- Interpretation of the users' input (prompt) and LLM-based selection of three to ten reasonable matches;
- 2- Provision of a larger list of candidates (usually between 50 and 100) ranked based on similarity scores calculated between the users' prompt and genera diagnoses. The system transfers the user input to vectors based on the embedding model, then uses cosine similarity to calculate the semantic similarity;
- 3- Provision of tips to improve users' prompts.

The LATS is built with the GeoGPT 72B model, which is trained on an open-source LLM Qwen-72B from Alibaba Group (Yang et al. 2025). The training process for the GeoGPT models consists of three key stages and is described in Stephenson et al. (2026).

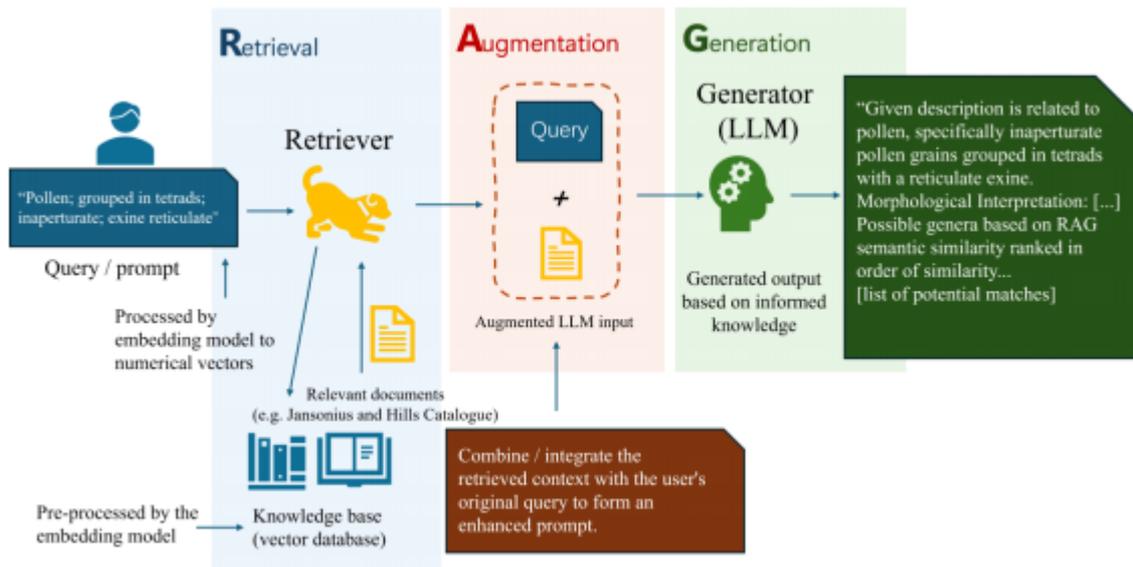


Fig. 2. RAG workflow for LATS (after Stephenson et al., 2026).

In order to compare the functioning and efficiency of the Brachiopod LATS using the synthetic Treatise genera diagnoses only, or the genera diagnoses integrated with the corresponding description of taxa of higher rank, a function was introduced to allow the user to select the information used by the LLM in the similarity score calculation. The user of the Brachiopod LATS can thus choose between two options: 1) LLM sorting through genera diagnoses integrated with description of corresponding taxa of family and order rank (tribe, subfamily, family, superfamily, suborder, order); 2) LLM sorting through genera diagnoses integrated with descriptions of corresponding taxa of family to subphylum rank (thus also including subclass, class, subphylum descriptions) (Fig. 3). In addition, to make the system more adaptable to the necessity and level of expertise of the user, the option to restrict the LLM search to a specific class (Lingulata, Paterinata, Craniata, Chileata, Obolellata, Kutorginata, Strophomenata, Rhynchonellata) was included.

Genus diagnosis in LATS database (entire):

Cyrtia: Nontransverse to transverse; lacking plications.

Ventribiconvex; ventral valve hemipyramidal, with catacline or procline interarea and narrowly elongate delthyrium; deltidium with medial foramen; ctenophoridium absent. Delthyrial plate and stegidial plates lacking; crural plates commonly well developed. Commonly with fold and sulcus; surface smooth or plicate; microornament of nonspinose capillae crossed by variably nodose growth lines; delthyrium occluded by deltidium, delthyrial plate, or stegidial plates; dental plates present; crural plates variably developed.

Lateral slopes plicate or costate; fold and sulcus commonly well developed; fine ornament, if present, capillate, pustulose, or imbricate; spinose ornament absent; ctenophoridium absent in early forms. Generally biconvex; generally transverse with moderately wide to extended straight hinge line; ribbing very fine to coarse; small dorsal and larger ventral interareas always developed; spiralia directed laterally or posterolaterally with primary lamellae parallel and close to sagittal plane; jugum absent; shell substance impunctate.

Rhynchonelliform brachiopods with fibrous, impunctate, punctate, or endopunctate, biconvex, strophic or astrophic shells, articulated by deltidodont or cyrtomatodont teeth and sockets buttressed by brachiophores or supported by parallel socket or hinge plates repeatedly converging to form septalium or cruralium; pedicle opening as delthyrium or rounded foramen; interareas and notothyrium commonly vestigial or absent, well developed in some derived groups; ventral muscle scars with posteromedial adductors flanked or enclosed by diductors and laterally placed adjustors; dental plates less commonly converging to form spondylium; dorsal adductor scars petaloid or grouped and quadripartite; crura present in later groups and commonly extended as spiralia or loops; mantle canal systems variable as saccate, digitate, pinnate, or lemniscate impressions.

Brachiopods with articulated calcitic shells, secondary layer basically fibrous; articulatory structures essentially a pair of ventral teeth and dorsal sockets on either side of median indentations (delthyrium and notothyrium respectively) of interareas.

Option 1:
Genus, family, order rank

Option 2:
Entire description

Fig. 3. The four options available to the user to regulate the quantity and provenance rank of the information for each genus employed by the LATS.

Operation of the system

The Brachiopod LATS is included into GeoGPT as one of the agents. It works as a chatbox where the user prompt is supposed to be a description of a brachiopod specimen (Fig. 4)

The user is encouraged to include a standard description, as complete as possible, with information about the specimen dimensions, morphology, shell structure, ornamentation and internal characters. The user can also select which kind of information the LLM will use for the query (genus diagnoses integrated with descriptions up to order rank description; genus diagnoses integrated with descriptions up to subphylum rank) and if the LLM should look for candidate genera in the entire database of genera or just through the ones of a specific class.

After submitting the query, the LATS replies first by providing a section of “Morphological Interpretation” of the prompt, in order for the user to be able to check the ability of the system to understand the prompt. Where this is not the case, the user would be able to check their prompt and modify its format and use of terminology to increase the LATS comprehension.

After this the LATS provides a list of three to ten, usually five “Matching Reference Records” proposed by the LLM in relation to the prompt description, alongside a rationale **for** why the genus was proposed. This section is concluded by an “Overview of Morphological Interpretation and Matching Results”.

A third section includes a wider list of candidate genera, “Possible brachiopod genera”, commonly including around 100 genera showing a calculated similarity. Top 5, Top 10 and Top 20 genera in terms of similarity score can be selected.

Each of the candidate names is also connected to a specific double column window providing a detailed morphological comparison between the prompt and the genus on the left, and the details derived from the Treatise (Stratigraphic range, Type species, Authorship, Treatise Diagnosis) on the right, including also the corresponding photographic plate from the Treatise.

Finally, the LATS reply is concluded by the “Suggestions for Improvement” and “Suggested Refined Query” which suggest the user what kind of information about the specimen under investigation would be possible to add in order to refine the query.

At this point, the user can either provide further information on the specimen, which is automatically integrated with the ones in the first prompt, choose to restrict the LLM search to just a subset of genera database (e.g., selecting a single Class only), or choose to reset the query and start a new one.

Preliminary testing by APC is showing the LATS has a satisfactory level of semantic understanding and provides reasonable candidate genera. Testing by a wider audience of experts and non-experts will be performed upon final development of the system.

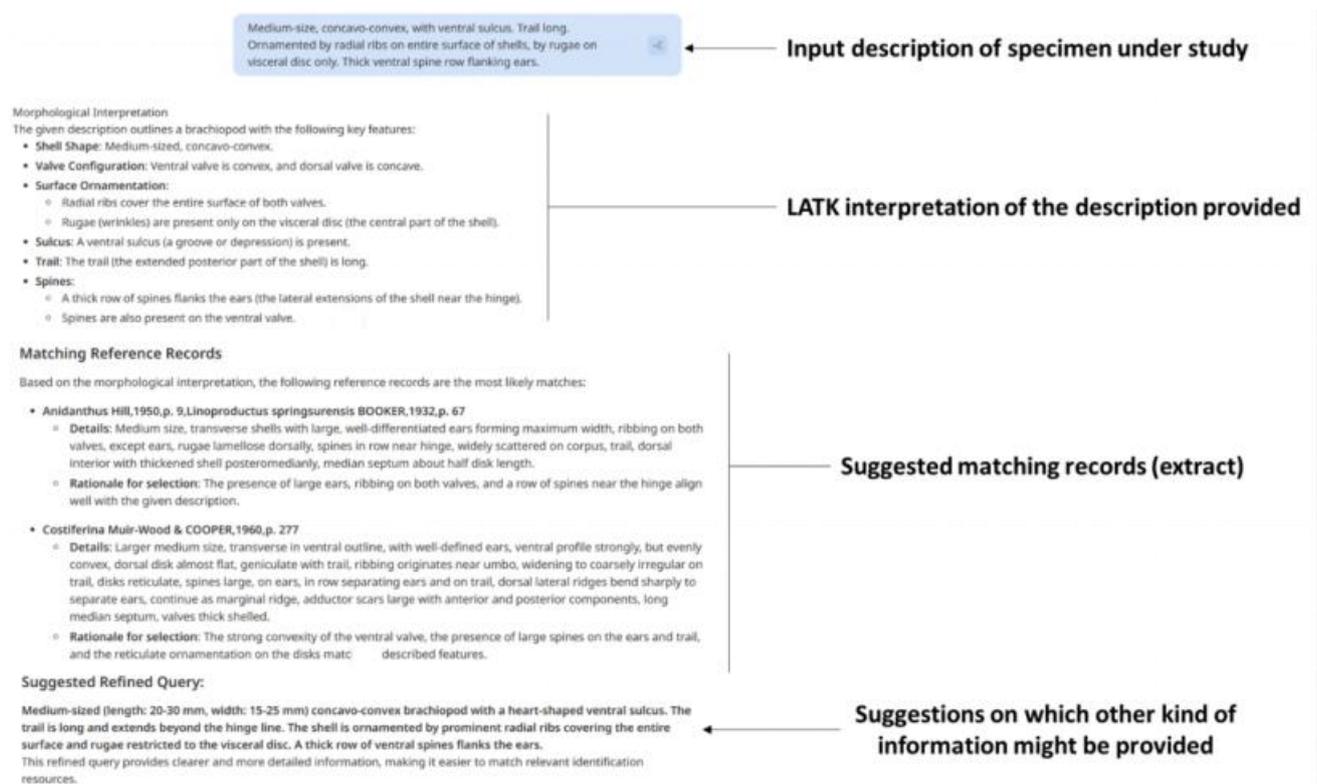


Fig. 4. Operation of the brachiopod LATS in GeoGPT.

Discussion

Efficacy of LLMs in taxonomy

The development of the Brachiopod LATS from the material in the Treatise of Invertebrate Paleontology and its efficiency in providing reasonable candidate genera proves the capacity of LLMs to successfully interpret morphological terminology and the potential of LLMs to be applied to the taxonomy of complex, 3D fossils such as brachiopods, also including features such as internal structures which cannot be easily documented in photographs. Another advantage of the application of LLMs to taxonomy in general is the capacity to manage a large number of taxa (almost 4200 genera are included in the Brachiopod LATS), a quantity which is unmatched by any other kind of automated system developed so far for fossil identification.

As already discussed in previous experiments of applications of LLMs to paleo-palynological taxonomy (Stephenson et al. 2025, 2026), LATS can assist the work of taxonomists, reducing misidentifications, as all genera in the database are taken into consideration by the LATS, allowing the recognition of possible synonyms defined in different stratigraphic intervals, and making taxonomy faster and more efficient. In the LATS the rationale for each candidate is shown to the user (i.e., the system is not a 'black box') meaning that the system can have a pivotal role in teaching taxonomic reasoning to early-career and unsupervised taxonomists. LATS could have a role in training new taxonomists especially in areas of the globe where a tradition of studies is not already rooted. Whilst paleontology moves towards the world of big data, geochemistry and macroevolution studies, taxonomists will still be needed not only to identify newly collected material, but also to define new unrecognized taxa and to preserve the stability and rules governing the classification system, the very foundation of paleontology.

Furthermore, LATS can also help expert taxonomists move into areas which they are less familiar with, like different stratigraphic intervals, making taxonomy a more dynamic and competitive field of science, tempting as a career option to early career researchers.

Hierarchical vs non-hierarchical systems

As is the case for the JH paleo-palynology LATS developed by Stephenson et al. (2026), the Brachiopod LATS developed during this study uses a Retrieval-Augmented Generation (RAG; Lewis et al., 2020) technique, searching for the best matches among all genera in the database based on the prompt. The system is thus 'flat', meaning the LLM does not follow any hierarchical scheme in its search and all characters in the diagnoses have the same weight in the calculation of the similarity score. However, in the case of the Brachiopod LATS, a hierarchical system is intrinsically present in the database as the genera diagnoses are merged with descriptions of the corresponding family to subphylum ranks; genera of the same taxa will have a higher similarity score due to the fact that most of their descriptions, apart from the part from the genera diagnosis, is exactly the same.

This does not affect the efficiency of the LATS as an aid to taxonomy. However, the intrinsic hierarchy reflecting the classification of brachiopods in the Treatise makes impossible to use this LATS for cluster analyses oriented to the investigation of morphospace occupation density to recognise synonyms, propose new classification and investigate morphospace occupation through time. Any analyses of this kind would be circular. Only a LATS trained with the original complete

diagnoses of all genera, like the JH palaeopalynology LATS, with no hierarchy in the data nor inserted by the authors of the LATS, could be used for cluster analyses to independently recognize and test taxonomic grouping and investigate morphospace occupation.

Given the fact that a hierarchy is already rooted in the data from the Treatise, and thus further research applications are not possible, it could have been theoretically possible to develop a LATK (LLMs Augmented Taxonomic Key) instead of a LATS, as the one developed by Stephenson et al. (2025) for a small number of Permian palynomorphs. In a LATK a decision tree for a polycotomic key is set based on a hierarchical system of character-questions to the user, guiding the user down to genus identification. A Brachiopod LATS was built instead of a LATK as it seems to be a more effective taxonomy assistant. A LATK, as any taxonomic key, might lead the user to a wrong set of candidate genera if some of the key steps-questions are misinterpreted by the user, which is possible especially in case of non-experts or early career scientists. This is against the principle of inclusion, stating that all reasonable candidate genera should be presented to the user. In the case of invertebrate fossils, taxonomic keys are impractical and not much used, as not applicable where some of the key characters are not available or visible for preservation issues. Also, while a hierarchical key can be easily developed for a small set of taxa differing among one another just for a few characters, development of a uniform key for all 4200 genera in brachiopods would be impossible, and specific keys for each class or order should be developed. To do so, expertise on each brachiopod group would be required, and the final result would in the end just reflect the opinion of the authors on the taxonomy of that specific group. While this would be theoretically possible to do in the current Brachiopod TA such an action would lack authority, be against the Principle of non intervention stated above, and require a considerable, and in end useless, effort.

Future prospects

The Brachiopod LATS presented here, prepared based on the data from the Treatise Part H Brachiopoda, Revised volumes (Williams et al., 1997, 2000, 2002, 2006, 2007) represents a benchmark for the development of similar LATS for other fossil groups developed based on the Treatise of Invertebrate Paleontology, and from similar taxonomic catalogues presenting synthetic diagnoses of taxa in a hierarchical system, instead of a database of full genera diagnoses as the case of Jansonius and Hills (1967). All other parts of the Treatise of Invertebrate Paleontology present a glossary of morphological terms, which can be employed to train LLMs to understand technical terms, and a structure of information identical in all volumes (Histon in Selden et al., 2025), so the same approach presented in this study can be employed. The main problem is represented by the quality of the primary source, as many parts are outdated and lack substantial number of genera developed in the last decades (Table 1).

Part	Fossil group	Published	Revised
A	Introduction: Taphonomy, Biogeography and Biostratigraphy	1979	No
B	Protista 1: Charophyta, Chrysomonadida, Coccolithophorida, Diatomacea, Pyrrhophyta	2005	No
C	Protista 2: Sarcodina (Including Foraminifera)	1964	No
D	Protista 3: Protozoa (Radiolaria, Tintinnina)	1954	No
E	Porifera	1955	1972-2015
F	Coelenterata	1956; 1981(Supplement)	No

G	Bryozoa	1953	1983 (pars)
H	Brachiopoda	1965	1997-2007
I	Mollusca 1: Scaphopoda, Amphineura, Monoplacophora, Gastropoda	1960	No
K	Mollusca 3: Cephalopoda (Endoceratoidea, Actinoceratoidea, Nautiloidea, Bactritoidea)	1964	No
L	Mollusca 4: Cephalopoda (Ammonoidea)	1957	1996, 2009 (pars)
M	Mollusca 5: Coleoidea	/	/
N	Mollusca 6: Bivalvia	1969-1971	No
O	Arthropoda 1: Protarthropoda, Euarthropoda (including Trilobita)	1997	No
P	Arthropoda 2: Chelicerata, Pycnogonida, Palaeoisopus	1955	No
Q	Arthropoda 3: Ostracoda	1961	No
R	Arthropoda 4: Other Crustacea, Myriapoda, Hexapoda	1969	No
S	Echinodermata 1: Homalozoa, Crinozoa (no Crinoidea)	1967	No
T	Echinodermata 2: Crinoidea	1978	2011
U	Echinodermata 3: Asterozoans, Echinozoans	1966	No
V	Graptolithina	1970	No
W	Miscellanea: Conodonts, Worms, Trace Fossils, Problematica	1962	1975-1981

Table 1. Overview on structure and date of publications of the Treatise of Invertebrate Paleontology.

Developing a number of LATS from data in the Treatise would currently be the easiest way to develop taxonomy assistants for invertebrate fossils, as in most cases databases of original, full diagnoses of genera do not exist. Building a LATS based on original, complete genus diagnoses would require thus first to collect all the material from the published monographs, books and papers, facing a number of problems including difficulty of access and data extraction from some monographs published in the 19th century and recent papers under a paywall. Furthermore, a number of problems similar to those faced by Stephenson et al. (2026) in developing the JH palaeopalynology LATS, but exasperated by the longer tradition of study of invertebrate paleontology, would have to be faced: lack of uniform style of diagnoses and descriptions, inconsistent use of terminology in publications from different periods, geographic areas and even published in different languages, and diagnoses of genera defined in the 18th and 19th centuries commonly not of acceptable quality for discrimination, meaning later emendations would have to be considered.

Despite these problems, the development of LATSs for the identification of invertebrate fossils based on databases of original descriptions extracted from the literature would be highly valuable. Such systems could function as more efficient assistants for taxonomists and as useful research tools. Secondly, they could serve as online, open-access and searchable databases of genera based on LATS architecture, which could be continuously updated with diagnoses of newly published genera as well as with emended diagnoses. Such systems would help overcome the well-known difficulty of updating volumes of the Treatise. In doing so, they could provide the taxonomic community with a unified reference framework, making the work of taxonomists worldwide more cohesive and collaborative.

A further step would be the integration of these LATS with deep learning models trained on images of fossil specimens. In such a system, the prompt could include both textual descriptions and photographs of the specimens under investigation. The system could then generate a list of

candidate taxa together with an explanatory rationale, based on the combined use of retrieval-augmented generation (RAG) and image analysis. Because the LATS would be trained on morphological terminology, it could recognize diagnostic features in photographs and translate them into structured textual descriptions. These descriptions could then be compared with those contained in the database of original diagnoses. The system would ultimately present the taxonomist with a transparent chain of reasoning supporting the proposed identification. Importantly, systems of this kind—grounded in databases of original descriptions and trained on the textual diagnoses of type specimens—would retain a strong link to the primary, authoritative taxonomic literature. This would provide a level of authority to the identifications produced and help preserve the stability of the nomenclatural system (ICNZ 1999; Turland et al., 2025).

A LATS trained with a database of original diagnoses of brachiopod genera extracted from the literature is currently under preparation.

Conclusions

The development of a LATS (LLM Augmented Taxonomy Sistem), based on descriptions extracted from the *Treatise of Invertebrate Paleontology, Part H: Brachiopoda, Revised* (Williams et al., 1997, 2000, 2002, 2006, 2007) provides a benchmark for the application of LLM to invertebrate fossil taxonomy.

The *Treatise* volumes include a glossary of morphological terms, employed to train the LLM, and an almost complete set of synthetic diagnoses of genera emended by a joint team of experts, thus of globally-recognized authority. To overcome the issue of the shortness of the diagnoses strategies were implemented such as integration with descriptions of higher-rank taxa and adjustable retrieval knowledge basis.

LATS are a valid option to develop automated assistants for invertebrate fossil identifications as they can easily cope with fine details of ornamentation, internal structures, and sort through a large number of taxa. A non-hierarchical system using a RAG is preferable to a hierarchical system employing a polychotomic key to avoid errors by non-experts at some point in the workflow and deal with incomplete specimens.

The next step for the application of LATS to invertebrate paleontology would be developing a LATS based on databases of original genera diagnoses extracted from the literature, eventually integrated with image-analyses systems, resulting in an efficient tool for fossil identification, research applications and open-access, continuously updated databases fossil genera.

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