

## **THE TENTELIC THESIS, INTERDISCIPLINARITY, AND EARTH SYSTEM SCIENCE: HOW NATURAL HISTORY COLLECTIONS UNDERPIN GEOBIOLOGY**

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The Tentelic Thesis explicates the attributes and roles of collections of preserved natural science specimens in epistemology. Combining the Latin roots *Tena* (to hold) with *Tela* (a web), tentelism describes how specimens inform the sciences; specimen preservation maintains the fecundity, fidelity and veracity of both existing and future knowledge. Natural science collections preserve tentelic specimens as the focal sources of scientific verification and innovation.

The tentelic attributes of specimens hold two interfacing roles in the changing landscape of science. They maintain the veracity of existing knowledge; and they equally catalyse new discoveries across the frontiers of scientific exploration. Alongside verifying and refining published knowledge, tentelic specimens are centrally positioned to support and inform a spectrum of unanticipated discoveries.

The maturation of 21st century science expands and elevates the core roles of collections in generating knowledge. Burgeoning refinements in analytical methods enable new insights from old specimens. Advances in methods developed in the Earth and life sciences are exemplified in how analytical instrumentation quantifies minerals, biochemicals and organismal structure at the molecular scale. These advances hinge on refinements of the Principles of Specificity, which increase the resolution and precision of scientific methodologies. Continuing advances in genomics and geochemistry open up new opportunities to explore collections, and in driving the emerging integration of the earth and life sciences, increase the relevance and scope of the Tentelic Thesis. I argue these developments are focused in the emergence of geobiology, which consolidates Earth System science.

Geobiology creates unprecedented opportunities to integrate tentelic information in biodiversity collections into a geological framework. This is because the chain of epistemic dependency extends from collections through natural history to support earth system science.

Collecting and preserving are still the core operations in natural history, ever since these roles became established in the 19th century. To avoid

repeating past mistakes, we need to understand the significance of this emerging consolidation of natural history, because the triumphant voyage of the sciences through the 20th century carried natural history as a barely tolerated stowaway.

Continuing progress in analytical applications by improving access to collections, is set to expand applications of genetic evidence across Earth systems. The emergence of geobiology teaches us how the armamentarium of molecular tools opens up unforeseen opportunities: empowering re-examinations of old specimens that allow us to ask entirely new questions. The history of science reminds us that we can only guess at future methods and questions. The challenges of Earth Stewardship in the Anthropocene underscore the importance of this quest, especially where it bears on the ecological integrity of Earth's Critical Zone and biodiversity conservation.

## **ТЕНТЕЛИЧЕСКИЙ ТЕЗИС, МЕЖДИСЦИПЛИНАРНОСТЬ И СИСТЕМА НАУК О ЗЕМЛЕ: КАК ЕСТЕСТВЕННОНАУЧНЫЕ КОЛЛЕКЦИИ ПОДДЕРЖИВАЮТ ГЕОБИОЛОГИЮ**

**Фентон П.Д. Коттерилл**

Тентелический тезис эксплицирует характеристики и значение естественнонаучных коллекций в эпистемологии. Объединяя латинские корни *tenu* (удерживать) и *tela* (паутина), тентелизм подчёркивает информационное значение коллекционных экземпляров в науке: их сохранение обеспечивают плодотворность, точность и истинность как существующего, так и будущего научного знания. Естественнонаучные коллекции обеспечивают сохранение тентелических экземпляров в качестве ключевых средств верификации прежнего и получения нового научного знания.

Тентелические атрибуты экземпляров выполняют две сопряжённые функции меняющегося научного ландшафта. Они поддерживают истинность имеющихся знаний и вместе с тем катализируют новые открытия в междисциплинарных научных исследованиях; это является наиболее значимым атрибутом музейного экземпляра.

Созревание науки XXI в. расширяет и повышает ключевую роль коллекций в формировании знаний. Расширяющиеся возможности аналитических методов в науках о Земле и жизни позволяют извлекать новое знание из старых экземпляров, относящиеся к минералам, биохимическим и организменным структурам на молекулярном уровне. Эти достижения зависят от уточнённой трактовки принципа специфичности, который увеличивают разрешающие возможности и точность научных методологий. Новые методы геномики и геохимии открывают новые возможности для изучения коллекций, повышая актуальность и масштабы тентелического тезиса прежде всего там, где происходит объединение наук о Земле и жизни. Это объединение знаменует собой появление геобиологии как важного раздела наук о Земле.

Геобиология открывает беспрецедентные возможности для интеграции тентелической информации, содержащихся в коллекциях по биоразнообразию, в геологический контекст. В этом проявляется эпистемическая всеобщность геобиологии, вовлекающей коллекции в развитие наук о Земле.

Сбор и сохранение коллекций по-прежнему имеет то же ключевое значение в естественной истории, которое утвердилось в XIX в. Чтобы избежать повторения прошлых ошибок, мы должны понять новое консолидирующее значение естественной истории, отодвинутой на периферию естествознания в XX в. в основном вследствие доминирования молекулярной биологии и экологии.

Рост наук о Земле, и в частности геобиологии, повышает значение естественнонаучных коллекций. В XXI в. они позволят наукам о Земле и жизни количественно оценить темпы и формы развития Земли.

Прогресс в области аналитического инструментария повышает доступ к коллекциям, что расширяет применение тентелических данных по всем земным системам. Появление геобиологии показывает, каким образом разработка новых молекулярных методов открывает невиданные возможности: новые исследования старых коллекционных материалов позволяют задавать совершенно новые вопросы. История науки учит нас, что мы можем только догадываться о будущих методах и вопросах. Современный этап активного освоения планетарных ресурсов, открывающий начало антропоцена, подчеркивает важность изысканий, тесно связанных с экологической цельностью критической зоны Земли и сохранением биоразнообразия.

## 1. Introduction

“The generation of diversity by cladogenesis furnishes every population with a unique set of historical legacies. In this sense an organism is a living record of its own history. In addition to whatever other values it may have, it has the same value as any other historical document. The loss of the Stellar sea cow and the Adam-and-Eve orchid were the same kind of loss to historical scholarship as the burning of the library at Alexandria”.

(Williams, 1992, p, 76)

Earth system processes interlink exosphere, hydrosphere, biosphere, geosphere, and the magnetosphere, and Life holds a pivotal role in their interplay; since Archaean times, abiotic and biotic processes have shaped the geobiology of the Critical Zone. Understanding these phenomena endorses interdisciplinary research. More critically, demands for credible research prescribe that

scientists collect and preserve specimens; whether specialist or interdisciplinary, any study of any facet of this complexity depends fundamentally on collections of organisms and minerals: comprising the vast diversity of objects preserved in natural science collections. What underlying epistemic relationships link all natural sciences so tightly to these preserved specimens?

The Tentelic Thesis explicates the roles of preserved natural science specimens in generating and maintaining reliable knowledge of the natural world in all its complexities. In any science, collecting, analysing and reporting observations and any other data carries fundamental responsibilities. These activities interrelate the: (1) qualities of primary data, especially veracity of observations; (2) independent and recurring reappraisals to verify data authenticity; (3) enable consen-

sibility among all data informing scientific knowledge; and (4) collections propagate epistemic fecundity by availing new observations on old specimens. These core epistemic standards prescribe why scientists continue to build on the great collections assembled since the dawn of the Enlightenment.

Today, we continue to collect and preserve specimens in order to vouch for published data, and our ongoing studies of established collections yield new data. The billions of specimens comprising the World's collections vouch for the veracity of the web of primary, baseline knowledge, and ultimately underpin the scope and robustness of nomothetic knowledge (Cotterill, Foissner, 2010). The state of 21st century science makes it timely to reevaluate the irreplaceable roles and values of natural science specimens. Genomics and geobiology and earth system science stand out in reshaping the landscape of all the natural sciences; and we need to ask how these impacts change the sphere of causal influence in which specimens maintain and advance sensible science. The answers turn out to hold major implications for the relevance of the Tentelic Thesis.

We first need to outline the broader context of this paper, by revisiting the significance of natural science collections. Inclusive of their diversity of biotic and abiotic specimens, natural science collections deal in historical contingency. Natural history empowers scientists with the universal suite of theory and methods to integrate historical evidence preserved in tissues, genomes and minerals. The science of natural history interlinks each of the world's natural science collections — each node a library — into a vast system of knowledge. This situation where all biotic and geological phenomena are ultimately the result of contingency, caused by events in Earth history, explains why the epistemology of biology and geol-

ogy depends in fundamental ways on collections.

Each of the myriad of specialized collections in scientific institutions comprises many different objects in its respective denomination (where object is a specimen of any historical provenance); here I inject the term 'denomination' deliberately; in a natural science, it is the provenance of a collection of objects that prescribes its denomination. As the outcomes of their individual phylogenetic, biogeochemical, or geochemical histories, the derived affinities of objects stand out in two complementary facets of their uniqueness — both shaped by natural history. The currency of denomination is set within outer phylogenetic affinities of historical provenance (e. g. Mammalia, Mollusca or Mantophasmatoidea, or mantle, extraterrestrial, igneous or sedimentary, Himalayan metamorphic). As samples of natural individuals that have evolved in the earth system, specimens form clusters of related populations affiliated by their shared origins. We are familiar with the individual collections of Insecta, Arachnida, Mollusca and Bryophyta, as equally as we distinguish complementary collections of living and fossil Mollusca, and the Apollo collections of Moon rocks. Analogous to biological individuals (species and phyla), a metamorphic, igneous, or sedimentary rock has a unique origin in geological history. Thus, complementing its palaeontological collections, a geological department will house collections of meteorites alongside the specimens of igneous, metamorphic and sedimentary rocks. Their respective dominations collectively vouch for objects of diverse provenance.

The fundamental epistemic roles of preserved specimens are highlighted in how they maintain and improve the precision of taxonomy. This indivisible interdependency of naming and classification demonstrates

how all facets of all biological and geological knowledge ultimately trace back to one (or more) specimens as unique tentelic sources of verification. Equally, an accurate taxonomy maintains sensible knowledge in supporting communication of accurate and precise information. Consensibility is a core credential of credible science (cf. Ziman, 1978; Cotterill, 1999, 2002a).

These few examples, set within the myriad, illustrate how the strictures of historical origins dictate why scientists must collect and preserve. Nevertheless, we must probe deeper to explain why collections qualify as such remarkable and irreplaceable resources informing science and civilizations. Here, fortuitously, we can start from the platform established on the principle of historical contingency, which undergirds and distinguishes natural history as a core science. And this is where the Tentelic Thesis explains why each natural science specimen stands apart as a unique and irreplaceable object. It further explains the unique epistemological processes entailed in specimen preservation. The Tentelic Thesis is grounded in the principles of historicity; inexorably, the epistemological attributes of the specimen reflect on the unique attributes of its ontology — encapsulated in its origins.

What is the relevance of the Tentelic Thesis to the natural sciences as a whole? The credibility of a scientific theory is determined by its ability to explain one (or more) set of generalities. Any generality described by a scientific theory comprises a cluster of idiographic data. The veracity of each individual data point sets deeper controls on the validity of an interpreted generality and thus a theory. As scientists, we undertake critical checks on data veracity. This is (or should be!) a fundamental epistemological operation, whereby scientists discover, derive and test theories.

A pertinent example is how the accuracy and precision of palaeoclimatic curves are determined by their summaries of series of collated data points, quantified by different specialists in analyses of sediment and ice cores. The need for independent and/or future checks of individual measurements of proxies (e. g. stable isotopes) and biostratigraphic markers (including taxonomy of marine organisms) demand that investigators facilitate opportunities for independent researchers to examine the primary sources of data. In this particular example, it is the drill core maintained in a geological collection. The strictures of historicity engender these fundamental epistemological challenges. The inescapable constraints embodied in the nature of historical processes are pervasive: with widespread and multitudinous impacts. They can be summarized in the statement of ‘the ubiquitous of uniqueness’. Fundamentally, they explain why scientific specimens preserved in collections enable repeated referrals and follow ups by independent researchers, each affiliated to their specialities. Tentelism dictates why space, earth and life scientists must collect and preserve specimens, wherever they seek to elucidate historical phenomena.

What is the derivation of the word “tentelic”? Formulation of this argument (Cotterill, 1995, 1997a, 1999, 2002a), lead from my surprise in discovering science had no succinct, pithy concept, with which to describe the formal roles of preserved specimens in maintaining the veracity of scientific knowledge. I proposed the complementary neologisms, *tentelic* and *scientela*:

“...such that a preserved, correctly documented specimen preserves tokens of tentelic information; and so contributes a unique detail of reliable information to a web of knowledge assembled by biologists about life. Such tokens of tentelic information include its occurrence, identity, and age. The neologism,

scientela, describes this composite web of authentic knowledge about biodiversity, built of tentelic information. Singular properties of the scientela are consensibility and authenticity, where authenticity is built from reliable and representative tokens of tentelic information. Literally, the scientela is the “web of knowledge”, while the verb, tentela means “to hold together the web of knowledge”. The most critical epistemological contribution in biology of preserved specimens is their operation as tentelic tokens of reliable information” (Cotterill, 2002a, p. 254).

Building on the above, a synthesis of subjects structure this essay to revise the ultimate scope of the Tentelic Thesis. They all have a major bearing on the credentials of natural history, re-establishing its scientific status in the 21st century, despite its neglect and eclipse across science through the latter half of the 20th century. This history of its shifting status deserves to become generally known, and has major lessons for we teach and support science.

Moreover, belated scrutiny of the Eclipse of Natural History across the life sciences highlights the credentials of molecular biology and proteomics — and geochemistry — in shaping the New Molecular Natural History. Maturation of the methodology of these sciences positions them to make widespread and fruitful uses of natural science collections; moreover, studies of molecular biodiversity are beholden to collect and preserve vouchers of their individual subjects. This new natural history cannot ignore the fundamental roles of tentelic specimens in vouching for “Molecular Fingerprints of the Evolving Earth”.

All in all, mainstream science can no longer afford to treat natural history as at best a peripheral curiosity. Those 21st century scientists seriously committed to understanding Earth history require multiple bodies of evidence of biotic and abiotic phenomena.

Combining the epistemological attributes of natural history with the raw data and tentelic support of collections is pivotal to make sense of the tempo and mode of the spectrum of evolutionary events.

This argument opens up a more ambitious goal to examine how the Tentelic Thesis interfaces with the earth sciences, especially where evidence preserved in biodiversity collections interfaces with geological evidence—in a geobiological context. Set in the milieu of the challenges and expansion of 21st century science, the rise of geobiology broadens the roles of tentelic specimens in supporting and consolidating explorations of the evolving Earth. This broader overview must also embrace the developments in genomics and Earth System Science (as defined by Earth System Sciences Committee, 1988; Condie, 2005; Dadson, 2010). Anthropogenic impacts on Earth System underwrite the timeliness of geobiology. All these developments underscore why the future for natural science collections is so exciting and rich in opportunity.

Overall, the development of geobiology is interlinking several previously independent arenas of scientific research. Here, I define a link as the epistemological connection between two or more scientific disciplines and/or subjects. Such links between the more remote of these disciplines are yielding the most exciting discoveries in geobiology. Natural science collections are key to support these interdisciplinary developments.

This global overview confers two further benefits. One, it enables us to integrate a vast cluster of associated disciplines into the framework of Earth System science. Second, the spatial domain of the biosphere sets the real world framework to evaluate the overall relevance of all natural science collections, including geological specimens originating in the abiotic geosphere and outer space. To-

gether, this synthesis positions us to appreciate unique roles preserved specimens hold throughout the epistemology of the natural sciences. Moreover, it follows that no science engaged in the quest to understand any facet of biospheric complexity, nor the complexity of the evolving Earth System, can ignore the fundamental epistemological principles embodied in the Tentelic Thesis. Its epistemological breadth integrates the earth and life sciences. These indivisible causal links, exemplified in geobiology, straddle Earth System science. The latter's interdisciplinary scope subsumes all the geological and biological sciences.

My review of these topics unfolds through two main sections. Part I describes the credentials of the Tentelic Thesis and the status of Natural History. I ask how the main focus of scientific research through the 20th century caused the eclipse of this core science across academia. Part II examines how refinements in resolution and precision in the instrumentation of 21st century science catalyse the burgeoning integration of the earth and life sciences. The new research opportunities driving this groundshift across the natural sciences open up many new uses for old specimens. They expand the scope of the Tentelic Thesis.

## **2. The Tentelic Thesis, the state of natural history and eclipse from science**

### **2.1. Tentelic specimens: information preservation into the future**

The series of papers that developed the Tentelic Thesis (Cotterill, 1994, 1995, 1997a, 1999, 2002a; Cotterill, Dangerfield, 1997; Cotterill, Foissner, 2010) spelt out the keystone roles of natural science specimens in epistemology. In summary:

*Specimens preserve complex information.* Each multicellular organism is unique

(Cotterill, 2002a; Mayr, 2004) and each biological specimen is an original sample from a population comprising organismal biodiversity. In its preserved form, a specimen is the best known means to preserve the complex information represented in its genetic and phenotypic traits (Cotterill, 1995, 1997a). New opportunities to study previously inaccessible properties of specimens (especially their preserved molecules) now allow unprecedented insights into biological variety. These continue to be facilitated by technological developments. Given novel accessibility to the properties of specimens, it is difficult to predict future uses and thus categorise values of specimens based solely on their current uses.

*Historical information preserved in collections ramifies through science.* The individual constitution, together with a singular origin in time and space, confers a unique historicity on each specimen. Replacement of a specimen is impossible. Different groups of specimens, originally studied within their respective sub-disciplines, are equally essential in many other life sciences. For example, present uses of botanical specimens extend beyond floristics; they are the sources (and refutable vouchers) of biogeographical, systematic, ecological, and biochemical information, which interrelate with numerous other domains of biological knowledge.

*Information derived from natural science specimens maintains knowledge.* In addition to the myriad of uses of specimens throughout the life sciences, their preservation maintains data quality. This is critical. For biologists to disseminate knowledge about organisms, such as individual plant species, taxonomies allow disparate facts to be collated, compared, synthesised, and also refuted. In epistemological terms, taxonomies maintain consensibility (see Ziman, 1978) across sciences and wherever else knowledge

is applied. Here, types vouch for Linnaean binomials to allow universal communication of disparately derived data. Underpinning the construction and maintenance of taxonomies, preserved specimens are fundamental to authenticate independently derived facets of information - whether an identity, relationship or other property published about an organism and its circumstances of existence. These epistemological functions of specimens, as unique sources of historical information, underpin a web of sensible knowledge about the living world. Tentelism establishes the unique role of specimens in science.

Tentelic attributes of specimens operate in multifarious ways. For example, integral to vouching for all natural history data of individual species, all these values are magnified by the dependency of biodiversity maps on collection coverage; every georeferenced geographical record matters in reconstructions of biogeographical patterns. The many, acute gaps in distributional data weaken the coverage of biodiversity maps. This uncompleted state of knowledge — the Wallacean Enterprize — is embodied in the acute deficiencies in our knowledge of species' distributions. It endorses unprecedented biodiversity surveys (cf. Lomolino, 2004; Herkt et al., 2016). In short, the primary roles held by specimens in shaping the Tentelic Thesis undergird all subdisciplines of biology and geobiology: wherever we explore any facet of the Critical Zone in the evolving Earth System.

## 2.2. The path to the Tentelic Thesis

Before delving further into how collections relate to Earth System complexity, it is useful to summarize the origins of the Tentelic Thesis. This summary helps to place natural science collections and natural history into the context of modern science.

Early in 1992, in no lack of crisis, my interest in natural science collections came to

a head. I soon realized the very real threats to the continued existence of these collections, and associated taxonomic expertise, are embodied in the metaphor of the Alexandrian Tragedy — irreplaceable losses of scientific libraries preserving unique evolutionary information. Its impacts across the sciences are multifarious (Cotterill, 1997a,b). The impacts on biodiversity research and taxonomy are appropriately termed the Taxonomic Impediment (Hoagland, 1996; Dubois, 2010). Grappling with these issues as Curator of Mammals, employed in the Natural History Museum of Zimbabwe, Bulawayo (NMZB), I soon realised the magnitude of a global crisis.

The obvious route to raising appreciation of collections lay in presenting a counter argument. Such an explication had to elevate the values of collections and all dependent science in the eyes of funders and administrators. The quest for this argument highlighted the fundamental questions asking what collections stood for. What is the real scientific value of a natural science specimen? Is natural history a science, and if yes, why? What are the ontological and epistemological credentials of natural history? Most pertinently, how do collections fit into the epistemology of science?

Burrowing into the philosophy of science, my quest for answers ransacked the literature of museum based journals and the life sciences. The few articles on values of collections in museum-focused journals shed little real light beyond the alarm and handwringing: replete in repeated complaints and frustrations. Nevertheless, the role of specimens as vouchers of data, and their support of taxonomy stood out as relatively well known — but only among a minority of museum-based scientists. I gained some traction from stimulating discussions at the UNEP Expert Conference on Biodiversity (Trondheim), and then soon after,



when I passed through Cambridge in June 1993. On Trinity Street, in the famous Heffers Bookshop, my eye fell on *Natural Selection: Domains, levels and Challenges* by George C Williams (1926–2010); alongside the lucid, highly influential *Adaptation and Natural Selection* (Williams, 1966), both books rank as classics in evolutionary biology. The insights and principles they espouse are ever more relevant to navigate the complexities thrown up in the natural sciences. Yet, today, I am shocked at the number of younger biologists, who have never heard of either book!

In emphasizing the significance of the Codical Domain of genetic inheritance, Williams (1992) defined and named Dretske's Principle to fix the lack of a principle explaining the conservation of information (in contrast to the conservation of matter). The bibliography cited the two key works by Dretske (1981, 1985). Soon, I was able to extrapolate on Dretske's philosophy. Now I was positioned to explicate the semiotic roles of preserved specimens in the epistemology of the natural sciences: with universal implications for all scientific operations (Cotterill, 1995, 1996, 1997a, 1999; Cotterill, Dangerfield, 1997; Cotterill, 2002a, 2003). Subsequent philosophical work on the species problem (Cotterill, 2002b, 2003a,b, 2006; Cotterill et al., 2014) uncovered the wider scope of tentelism; where the ubiquity of uniqueness underpinning the Tentelic Thesis interfaces with Michael Ghiselin's Individuality Thesis (Ghiselin, 1997; 2005a,b).

But to return to the mid-1990s, Williams cited the infamous conflagration of the Libraries of Alexandria as a metaphor of extinction. His highlighting the loss of unique evolutionary information struck a Pavlovian chord; especially when my relentless quest for context was rewarded yet again. Returning to Heffers Bookshop in Cambridge the

following year, I discovered Ayres (1994). Ayres extended information theory to integrate evolutionary economics with ecology, and much else besides; notwithstanding its deficiencies, this work remains an exemplary example of interdisciplinary synthesis. The opening phrase in the book leapt out at me — “Evolution as Accumulation of Useful Information”. I embedded this loaded phrase into the library metaphor to highlight a most worthy cause: recasting the stark state of museum collections as “The Second Alexandrian Tragedy” (Cotterill, 1997a).

By the late 1990s, the need for a pithy concept describing the informational role of preserved specimens in preserving scientific knowledge became all the more apparent. I was surprised no such concept existed. This was despite the considerable interest already being paid to an independent philosophy of biology (including the writings of David Hull, and Ernst Mayr, among others). The Latin roots of *Tela* (a web) and *Tena* (to hold) coined the apt neologism (Cotterill, 1999). More recently, a response to a particularly extreme case of woolly thinking, applied to biology (Baveye, 2009), invoked the articulation of the scientific status of natural history (Cotterill, Foissner, 2010).

This recent argument is grounded in my theory of tentelism, and it leans centrally on Ghiselin's Individuality Thesis. In important respects, the current paper builds on arguments I had synthesized by 1996, which explicated the roles — and thus socio-economic values — of natural science collections in biodiversity characterization (Cotterill, 1996). Most recently, an interesting example of a pioneering application of the Tentelic Thesis supported a novel legal decision in support of biodiversity conservation. This was the proclamation of a protected area to protect the ecological and geomorphological integrity of the shared type locality of nearly 100

genera and species of free-living protozoans (Anon., 2013; Cotterill et al., 2013).

### 2.3. Collections and natural history in paradoxical crisis

Nevertheless, the trends in funding and publishing suggest that the tenets and constraints of the Tentelic Thesis remain peripheral to mainstream interests and priorities in 21st century science. This prevailing attitude stands out in the *Pervasive Denigration of Natural History* (Cotterill, Foissner 2010). This strange situation is really remarkable, in fact bizarre, in the paradox undermining the integrity of 21st century science; especially when we consider the argument justifying the epistemological status of natural history. It is the core discipline maintaining the integrity of the earth and life sciences, and thus the latter's profiles in academia, societal support and publishing. Ultimately, they are all grounded in museum-based science. Arguably, more and more sciences are becoming all the more dependent on natural science collections, as the singular resource to maintain scientific integrity and push back frontiers of ignorance.

Here, the primary concerns underpinning these relationships between the sciences and collections centre on analytical rigour. The argument is bolstered by the growth and refinement in intensively analytical sciences to resolve the complexity of biotic and abiotic phenomena at the molecular scale (of genomes, cells — and — geochemicals and minerals, respectively). I argue that the pathway leading to this remarkable state of affairs can be traced back to the Golden Age of Molecular Biology (see Stent, 1968, 1969, 1970, 1985), which has also increased tensions between the molecular sciences versus both traditional geology and organismal biology. We can identify a parallel thread of history in how the quantitative prowess of the earth

sciences grew over the same decades; we see this progress in the status of geochemistry and geochemistry today. Never before, has science held such remarkable power in the unprecedented precision and resolving power of its instrumentation, whose automation is tightly dependent on digital technology (cf. Lee, 2014).

Yet, in contrast to this progress enabled by 21st century instrumentation, far too many museums and collections struggle forward in crisis. These institutions lack even the most basic support and staffing. The bigger picture of this paradoxical crisis — the Alexandrian Tragedy — positions academic traditions in a bizarre, counterproductive tension against innovate ideas and new opportunities in science: collectively empowered by unprecedented technology.

The irony and tensions arise where more traditional sciences meet the technologically intensive quests of molecular-based sciences (e. g. genomics). Asymmetrical support of the latter recognizes the prowess of their instrumentation, which has never been so powerful. Ironically, this bias overlooks how the great potential in these refined analytic methods positions earth and life scientists to explore the evolving Earth System in unprecedented depth and detail.

Although these exciting initiatives enrich the state of science, their penetration into its mainstream continues to be held back by recalcitrant barriers subdividing academia's ivory archipelago (cf. Roberts, 2001; Wilson, 2007). These barriers to integrate traditionally isolated disciplines persist in the comforts of conservatism. The paradox stands out where such integration is fundamental to realize the tentelic wealth of natural science collections in all its breadth and depth. This multifaceted paradox raises interesting questions, when one contrasts the state of academia against such an unprecedented

breadth and depth of opportunities. Here, the Alexandrian Tragedy and the Pervasive Denigration of Natural History highlight the state of pedagogy and scientific literacy in mainstream academia, and funding strategies responsible for directing public funds to support 21st century science.

#### **2.4. Planet Earth's Critical Zone: sources of collections**

First, we need to define the universal spatial framework that structures the overall provenance of the world's natural science collections. Vernadsky's concept of the Biosphere delimits the focal source and sphere of biological collecting; but the full scope of natural science collections includes all the abiotic specimens originating in the mantle and upper exosphere, as well as objects of extraterrestrial provenance. The spatio-temporal domain of the evolving Earth System sets the universal domain, which frames the many sources of specimens. Examples include meteorites, bubbles of ancient Earth's atmosphere preserved in fossils and ice cores, mantle rocks and other xenoliths, together with all biological and lithospheric specimens.

Increasingly, the concept of the biosphere is recast as the Critical Zone (cf. Amundson et al., 2007; Brantley et al., 2008; Lin, 2010; Brantley, Lebedeva, 2011; Rasmussen et al., 2011; Banwart et al., 2013). Considered in the Earth System framework, the Critical Zone encompasses each and every habitat supporting Life. This spatial domain of Life gives us the global context to map out origins of biodiversity collections, and specimens with geomorphological affinities. It comprises the landforms supporting biodiversity in landscapes and seascapes, and their abiotic and biotic parts. Definitions of the extent of the Critical Zone differ between disciplines.

This integrated definition — the Critical Zone embedded in the evolving Earth System — overcomes the parochial spatial and/or functional definitions specific to different disciplines; they each focus on one suite of surface, hydrological, subaerial and/or deeper habitats. The total spatial domain of subaerial and subterranean habitats includes the vadose and phreatic realms, the pedosphere, and all other subaerial domains comprising the regolith (using the regolith concept in its broadest context). The Critical Zone also extends across seascapes, notably marine sediments and the underlying upper portions of oceanic lithosphere into which water and dissolved gases and minerals reticulate (and/or are subducted). These domains sustain Life within the upper temperature “biopach”: contingent on the depth of the local geotherm. Equally, the outer spatial domain of the biosphere includes all the highly dynamic domains of the atmosphere inhabited by Life, notably aerial plankton and their predators, and migratory biodiversity (Kunz et al., 2008; Womack et al., 2010; Diehl, 2013; Smith, 2013). Populations of organisms persist in all these domains of the Critical Zone. Nevertheless, it is humbling to acknowledge that science is still mapping out the ultimate depths of the biopachs: the ecophysiological limits (including the extreme “osmopachs” of hyperhaline habitats, (cf. Stevenson et al. 2015) within which Life exists in the continental and oceanic lithosphere.

This entire spectrum of habitats supporting Life extends deep within the oceanic and continental lithosphere at the weathering fronts of rocks; at their greatest depths, these outermost boundaries to Life comprise the hot, deep biosphere. The fractal and/or near-fractal spatial topology of these habitats scale from the microscopic to the global domains of Earth's continental and oceanic plates, and it extends upward into the highly

dynamic domains of the atmosphere inhabited by organisms. In encompassing all biotic assemblages, the entirety of the Critical Zone includes all ecosystems that interlink the geosphere and exosphere. The greater portion of the Critical Zone comprises the Earth's regolith extending into the Deep, Dark Biosphere. It is the focal realm of the biogeochemical dynamics interlinking geosphere, hydrological and atmosphere.

Fractal boundaries shape distinct biotic and abiotic landscapes of the Critical Zone, and the geosphere, and exosphere, respectively, and these spatial units provide practicable guidelines to focus research questions and quests. This diversity of landscapes forms the collective domain explored by the many disciplines comprising the earth and life sciences. The specialities of individual scientists fall out across the vast range of opportunities presented in this collective domain, where often just one, or a few, research questions contain and guide a scientist's lifetime career. In many cases, a single domain (e. g. pedozone and vadose zone) focus a discipline's traditions, and prevailing paradigm. It is understandable why practical demands and resources contain one's attention to focus on only one, or a few, discrete facets in the spectrum of opportunities of landscapes and research subjects. Geomorphology, palynology, sedimentology, speleology, and the finer scaled subdisciplines of the life sciences are pertinent examples.

The full epistemic scope of natural science collections straddles all diverse facets in this material universe of the Earth System and Critical Zone. Individual specialists may find the context of this universal domain too remote, if not irrelevant. It is not surprising to see new initiatives in interdisciplinary research struggle to find acceptance and gain traction, where they embrace a broader range of challenges presenting in

the material complexity of the Earth System. Nevertheless, each body of discipline-specific knowledge is by no means isolated within the larger arena of complexity of the Earth System. Each science links into the whole, wherever respective taxonomies undergird biology, mineralogy, and petrology, and all their dependent knowledge.

Taxonomy is a good example of how tentelism enables us to map out the diversity of empirical evidence, within and across different bodies of interdependent knowledge. These classifications of preserved specimens of minerals, organisms (and fossils) can logically be integrated, especially over the timescale of the geological record, and/or in synthetic maps of landscapes. Consider, for example, soil samples (where some may exist only in reference type sections) and other specimens — including type localities — vouching for attributes of geomorphological landforms and geological formations, which inform classifications of soil and lithology on which maps of biodiversity are integrated. Although I have only summarized the rich diversity of the Critical Zone in brief, this overview paints out its complexity: in all the diversity of habitats and landscapes shaping the 3-dimensional spatial domain wherever Life can exist. Although specialized disciplines only study a discrete spatial domain and/or subjects, sciences collectively hold all that our species has come to know about the complexity of the biosphere, and its relationships with the evolving Earth System. Further treatment of this topic lies beyond the scope of this paper.

The message of this all too brief summary is relatively simple. It emphasizes: (1) research efforts across the vast diversity of physical (spatial) domains and biodiversity has to be partitioned to optimize efforts, but disciplines too often work in isolation; (2) all relevant sciences are unified in complementary quests

to explore this entirety of habitats throughout its 3-dimensional spaces — no matter how remote any science may appear in the focus of its local specializations; (3) vast regions of the Critical Zone remain barely explored; and (4) the overall extent of the Critical Zone frames and unifies the global coverage of all collections of natural science specimens.

Natural science collections provide Earth System science with its most tangible and robust suite of material proxies. We can study preserved specimens to map out what science has explored, and where and when a naturalist collected each of these facets of material evidence, and furthermore, we can estimate the times of ultimate origin of vouchers sampled through geological time.

### **2.5. T.H. Morgan's deviation: how did molecular biology eclipse Natural History?**

“The sciences in our century, to be sure, have been marked almost wherever one looks by momentous discoveries, by extraordinary people, by upheavals of understanding — by a dynamism that deserves to be called permanent revolution. Twice, especially, since 1900, scientists and their ideas have generated a transformation so broad and so deep that it touches everyone's most intimate sense of things. The first of these transformations was in physics, the second in biology. Between the two, we are most of us spontaneously more interested in the science of life; yet until now it is the history of the transformation of physics that has been told”.

(Judson, 2013: p. xxxi)

We now move on to establish why academia treated — and continues to treat — the science of natural history in widespread contempt. As recounted by Wilson (1994), molecular biology stands apart in its notorious disregard for natural history. The scientific importance of molecular biology needs no introduction and its inaugural history is narrated in detail (Stent, 1968, 1969, 1970; Morange, 1998; Judson, 2013). The above quote from

the *Eighth Day of Creation* (Horace Judson's remarkable book) hides more than a trace of irony, especially considering the peculiar situation of natural history. In contrast, the great advances that so dominated so many sciences through the last century, into the present, stand tall in contrast to the profile of natural history, whose decline has attracted repeated attention (e. g. Bartholomew, 1986; Donoghue, Alverson, 2000; Eisner, Wilcove, 2000; Beehler, 2009, 2011; Cotterill, Foissner, 2010; Dubois, 2010; Ricklefs, 2012; Tewksbury et al., 2014; Boero, 2015).

The anomaly that stands out in Judson's scoping statement is the failure to mention that other key sciences underwent their respective revolutions through the period inaugurated in the discovery of the DNA structure in 1953, and the rapid progress that unfolded over the 1960s in shaping the Golden Age of molecular biology. Consider the theory of plate tectonics, the rise of paleobiology and the consolidation of comparative biology on the foundations of Hennigian philosophy (see below). The tendency to overlook these sciences was often criticized by Stephen Jay Gould (Gould, 2002); for historical science is too often judged inferior to nomothetic science: with this tension encapsulated in the inferiority complex of biology — termed “physics envy”.

Subjective tensions aside, no comprehensive history of science can afford to overlook the consolidation of organismal biology, exemplified in the behavioural sciences pioneered by Lorenz and Tinbergen (Mayr, 1982). Most fundamentally, the upheaval that overturned hardwired phenetic approaches to classify biodiversity and inform comparative biology stands out. Inaugurated in Darwin's new world view, this rise of tree thinking (O'Hara, 1988, 1997) ranks in its own right as a revolution in philosophy, let alone science (Ghiselin, 1971, 2005a,b). Its impacts continue to play out in

taxonomic revisions informed by phylogenetic systematics. The penultimate epilogue in this revolution that has matured in modern systematics was catalysed by Hennig (1966).

Nevertheless, as is so obvious in the 21st century, the Genomics Revolution holds unprecedented profile in science and society. The outstanding progress gained in understanding Life in all its molecular intricacies stand out in media attention to how genomics has transformed our understanding of the natural world. Ironically, as we shall see, the maturation of the Molecular Biology Revolution highlights the pivotal values of the great collections of natural science specimens preserved in museums and herbaria, and genomics' future is embedded in natural history!

Equally, Judson all failed to acknowledge the remarkable progress that reconstituted the earth sciences through the 1950s and 1960s. It catalysed and focused the significant progress, we see in the analytical prowess of geochronology, geophysics and geochemistry, especially in their quantitative methods. All these advances are especially relevant to geobiology. The progress enabled by the Plate Tectonics Revolution (Frankel, 2012a–d) dovetailed with the maturation of geochronology. We see the impacts in the ability to date minerals with confidence as fundamental and radical to quantify events in Earth history. The impacts resolve and revise understanding of the Fossil Record and biotic evolution (Bowring, Erwin, 1998). Geochronology continues to be refined, especially in its precision (Schmitz, Kuiper, 2013; Schoene et al., 2013; Schoene et al., 2015). Equally, refinements in cosmogenic dating and thermochronology have injected new life into megageomorphology (Summerfield, 2005; Granger et al., 2013).

Now, let us to return to examine how, through the latter half of the 20th century, the other sciences eclipsed natural history. One chapter stands out in the *Eighth Day* in its

prospective analysis. Entitled *On T.H. Morgan's Deviation and the Secret of Life*, it is a synopsis of the state of molecular biology as it stood in the early 1970s. Presented as an Interlude after the first of the three major Acts narrating the origins of the science (Stent's "Golden Age") the chapter relies centrally on the author's interviews with Jacques Monod, Francis Crick and Sydney Brenner. The chapter's title refers to a key statement by Brenner, who described the Golden Age of molecular biology as "Morgan's Deviation". This metaphor describes how, early in the 20th century, the pioneering geneticist T.H. Morgan was forced to abandon his primary interest in developmental biology, because science first had to solve the mysteries of molecular inheritance and cellular organization. Only once the core mechanistic knowledge of Life was deciphered, could biology move beyond Morgan's Deviation. The successful outcomes are embodied in the tripartite theories of the Central Dogma, Sequence Hypothesis and Genetic Code. Since then, biology turned to open up new lines of attack on cell and developmental biology. I emphasize how this impressive progress is empowered by the refining of molecular methods; this refined instrumentation continues to improve on the remarkable automation and precision it has developed through the past decade.

We can best understand the founding history of molecular biology as the progress that refined the Principles of Specificity at the molecular level. This argument was first emphasized by Judson (1993, 2013). It underpins a central theme in this paper, and it focuses and strengthens its core messages. We see the most tangible benefits in the progress of developmental biology (among other life sciences) to attack their central problems, where major advances have increased since the 1970s.

No other hypothesis comes close to explain how molecular biology has established

its wide epistemological reach and power; the specificity obtained at the genomic level is embodied in our ability to read the sequences of chemical subunits with impressive precision, and decode molecular mechanisms embodied as sequence information. Biology's prowess in deciphering the codes of Life matured to dissect causes of molecular and cellular phenomena; and we can apply this understanding, outwards, far beyond the level of cellular organization. The applications are especially illuminating at organismal and higher levels (Judson, 1993, 2013). Remarkably, Judson's pithy explanation for the success of molecular biology seems to attract little, if any, of the attention it deserves. I emphasize its importance here, especially in its allied and direct impacts on natural history.

The circumstances that shaped the historical trajectory of discoveries to resolve and apply the Principle of Specificity began with "[t]he man who released the present-day understanding of molecular specificity was Frederick Sanger" (Judson, 2013, p. 585). By the early 1950s, Sanger had deciphered sufficient empirical evidence to reveal that the unique biochemical functions of proteins are determined by the sequence specificity of their aminoacids (Brownlee, 2014). In its illumination of potential concepts and mechanisms, Sanger's breakthrough rapidly catalysed ground-breaking discoveries: to elucidate the fundamental mechanisms of macromolecular interactions (Walker, 2014). An outstanding breakthrough stands tall in the formal articulation in 1957 of a universal manifesto for biology. This comprised the twinned proposals of the Sequence Hypothesis and the Central Dogma (Crick, 1958).

In one bold synthetic stroke, proposing mutually consilient theories, Crick's explanation encapsulated the core mechanisms

of information inheritance and translation; and most crucially, it explained how only a genetic code could explain inheritance (Judson, 2013). Informed by pioneering research in the 1930s and earlier, these pivotal breakthroughs refined the Principles of Specificity by ratcheting understanding upward across three major thresholds: (1) the discoveries in comparative protein sequencing by Sanger in 1951 that characterized shared, derived variations in their sequences (Brownlee, 2014); (2) the articulation of the Sequence Hypothesis and Central Dogma by Crick in 1957 (Crick, 1958); which (3) was subsequently validated by experiments and discoveries of the universal biochemical mechanisms of inheritance and protein synthesis; and the penultimate elucidation of the Genetic Code, finally completed by 1970 (Judson, 2013).

Another way to appreciate the universal relevance of the Principles of Specificity, spelled out by Judson (1994, 2013), is to recognize that they came to undergird the incorporation of Mendelian genetics (a phenomenological theory) into a mechanistic theory of molecular genetics. The Principles of Specificity remain all the more fundamental in modern biology. They explicate the keystone foundations of genomics, and all related subdisciplines (as classified by Baker 2013). Spelt out, they are:

- the linear sequences of biochemical residues (namely aminoacids, nucleic bases);
- the 3-dimensional structure of macromolecules that encode active sites (especially catalysis and allosteric induction);
- the specificity of the biotic codes represented in the diverse informational mechanisms of biosemiotics (cf. Barbieri, 2003, 2015).

The elucidation of the genetic code marked the foreclosure of molecular biology's classical period, if not its Golden Age (Stent, 1968). The discovery of Sanger Sequencing

(Sanger et al., 1977), a decade on, initiated a new growth pulse in molecular biology. The developments it catalysed surmounted major challenges, not least in reducing the costs and coverage of genotyping methods (Sanger, 1988; Judson, 2013; Berg, 2014; Brownlee, 2014). DNA sequencing technology received its greatest boost with the dovetailing of molecular tools with computational biology, where after digital technology proceeded to revolutionize genomics (Venter et al., 2003; Rogers, Venter, 2005).

As we all know, these advances in biotechnology underpin the exponential advances in the ability of biology to characterize entire genomes, and unabated progress continues to transform the biosciences (Venter et al., 2003; Mushegian, 2007; Stevens, 2012, 2013; Richardson, Stevens, 2015). By the 1980s, advances in biotechnology underpinned the swelling ground-shift in biology, which continue to rapidly refine the automation and precision of molecular methods to realize the practical potential embodied in the Principles of Molecular Specificity. Most critically, these advances empower progress in genomics and proteomics (Johnson, 2007; Baker, 2013; Stevens, 2013).

Nevertheless, although the triumphs of nomothetic science appeared to set molecular biology above other life sciences, it was soon realized that completion of Morgan's Deviation only marked a new — humbler — beginning for molecular and cell biology. Positioned beyond the strictures of Mendel's Deviation, all of molecular and cell biology now faced the complexities of the evolving organism, but, today, fortunately biotechnology has enabled these sciences to explore the molecular determinants of evolutionary mechanisms in more and more detail.

The real nature of this challenge had also become crystal clear by the end of the 20th century (if not earlier). By then, progress in

comparative genomics demonstrated that biotic complexity is only understandable through the lens of history. Ever since, molecular analyses have depended on systematics to place discoveries into evolutionary context. The application of these methods is relatively recent. This was because such applications were only possible by the end of the 1980s, once the consolidation of Hennigian philosophy and methods had firmly transformed the theory and practice of comparative biology.

Today, the scope and methods of phylogenetic systematics continue to strengthen and widen. Recent developments are exemplified in advances in Bayesian and Maximum Likelihood approaches, which resolve evolutionary problems from the scale of proteomics and cell biology to biogeography, ecology and macroevolution (DeSalle et al., 2013; Stevens, 2013). Utilizing genomic evidence to decipher the complexities of genomes, cells and organisms, phylogenetic systematics consolidates the feasibility of 21st century biology to explore the new frontiers that biologists began to first glimpse in the 1980s. To return to the first page of this paper, molecular biology has had to reconcile that its ultimate *raison d'être* is to decipher the intricacies of biochemical complexity generated by the *historical contingencies* of evolution. As I emphasize below, the events summarized in this paragraph have founded the new Molecular Natural History!

Although this philosophy reconciling with the pervasiveness of historical contingency is often paraphrased as “Nothing in biology makes sense except in the light of evolution” (Dobzhansky, 1973, and see Dilley, 2013), the most encompassing explanation I have yet to read between two covers is the book length treatment of Rose (1997). At all scales, evolutionary interpretations rule all biological explanation, and the passage of history



explains the Ubiquity of Uniqueness. It is why I emphasized this argument to label this state of affairs — a universal generality of biology — Darwin's Law (Cotterill 2002a, 2003a). The universal strictures and scope of Darwin's Law are underscored in the *Principles of Molecular Specificity*. It is why we can only understand differences between nucleic acid sequences as historical contingencies.

In so many ways, science is indebted to all the researchers who drove biology through Morgan's Deviation, to unearth the Principles of Specificity; today, their endeavours and discoveries underwrite the progress continuing to transmogrify biological knowledge in the continuing flood of discoveries. It shows no sign of slackening off, but continues to open up in the widening frontier, which embraces more and more of science (Judson, 2013; Stevens, 2013; Richardson, Stevens, 2015; Cotterill, in prep). The future is uncertain; it is impossible to predict how these new discoveries will play out, especially beyond biology. One impending outcome is clear. We see a most important and central domain of this expansion in the increasingly detailed exploration of the genomic record at a global scale (Cotterill, in prep). We see this in the flood of discoveries along expanding research frontiers across Earth's Critical Zone. It reveals the exciting corollary; the jurisdiction of genomics is no longer confined only within biology.

## **2.6. Ecology: eclipse of history versus deciphering Earth history**

Ecology holds a pivotal role in Earth System science. Nevertheless, the history of ecology also reveals curious deviations by its practitioners that lead the science away from the dictates of Darwin's Law. Biases in ecology impacted as badly on natural history as did those of classical molecular biology.

Ecology recently metamorphosed, maturing to use key methods and data, such that evolutionary history sets ultimate limits on neontological research explanations (i. e. attributes of extant ecosystems are determined by their historical origins); this dependency makes sound sense, when we acknowledge how historical contingencies ultimately determine all extant attributes of Life. Explanations of extant ecological phenomena have to seek deeper causes in phylogeny. Causal influences of phylogenetic constraints and innovations have come to be recognized as pivotal in explanations of not only ecological complexity but the origins of organismal diversity (Brooks, McLennan, 1991, 2002).

In summary, the ultimate control of ecological phenomena by historical contingency reflects how Darwin's Law underpins all organismal biology. Howsoever we study organisms, phylogeny structures all ideas and data. Phylogeny impacts across all scales: from the neontological realms of ecology and behaviour and ecophysiology, through to the broader arenas of paleontology and paleobiology (Cotterill, 2002a). The refined classification methods of phylogenetic systematics resolve the deep and broad epistemic scope of phylogenies (Cotterill, 2002a). As O'Hara (1988, 1997) argued so eloquently, systematics enables scientists to narrate the evolutionary chronicle.

The reconciliation of ecology with this reality can be seen in the interesting transformation of ecological journals over the past decade. More and more prominent papers published in active research areas rely on phylogenetic theory and methods. Comparative biology has consolidated its keystone position — conceptually and empirically; this strengthens both ecology and ethology. As with any biotic lineage, the ubiquity of uniqueness of species and biotic assem-

blages dictates why we can only understand new discoveries and competing hypotheses through the lens of history.

Yet, before quests for phylogenetic context came to link ecology so tightly with systematics, ecologists sidelined natural history. Stung by Lord Kelvin's stamp-collecting quip, and responding to the founding successes of molecular biology, biologists focusing on ecology and behaviour came to identify themselves more clearly as organismal biologists. Growing through the 1960s, ecologists made immense efforts to find nomothetic explanations — exemplified in assembly rules and competition theory — embodied in neontological mechanisms. Equally, physics-envy can be invoked to explain the focused investment in mathematical ecology, as evident in the contributions of MacArthur (1972). Brooks and McLennan (1991, 1999, 2002) argue that this phase in the growth of organismal biology caused an eclipse of history across much of the life sciences.

This eclipse was encapsulated in the state of ecology through the 1950s into 1980s. We can however understand how methodological challenges at the time catalysed this eclipse. Comparative biology did not have robust methods until the late 1970s (at the earliest). It was only in the late 1960s that English speaking taxonomists discovered Hennigian philosophy, following the publication of Hennig (1966); moreover, the theory and methods of cladistics took over two more decades to transform comparative biology fully, and it has required maturation of model based (likelihood methods) and applications of Bayes Theorem to consolidate the modern science of phylogenetic systematics (Felsenstein, 2004; Wiley, Liebermann, 2011).

In contrast to the eclipse of history, beginning in the 1960s, the new ideas and analyses of an emerging generation of palaeontolo-

gists and evolutionary biologists enabled a youthful science to revolutionize studies of the fossil record. This established paleobiology. Its important outcome can be seen in increased profiles of museum collections, not least by broadening cognisance of their values across the earth and life sciences. New interpretations of the fossil record have been matched in enhanced public appreciation and interest. Particularly, we can single out the discoveries of global mass extinctions (Raup, 1991), the theories of disparity and contingency (Gould, 1989), and the Effect Hypothesis (Vrba, 1993; Eldredge, 2005a,b). They continue to impact across evolutionary research. Overall, this new body of interpretations and theory developed in the Paleobiological Revolution revitalized the field of macroevolution (Gould, 2002; Allmon et al., 2009; Sepkoski, 2012, 2014; Sepkoski, Ruse, 2013; Eldredge, 2015a,b). We should not underestimate the impacts on the status of museum collections as the focal sources of all tentelic information that undergirds revised insights into the tempo and mode of macroevolution (see Cotterill, 2002a, and Eldredge, 2015a,b for some examples).

Here it is important to include the no less fascinating arena of interdisciplinary progress, which has transformed developmental biology. We see this in the integration of macroevolutionary theory and evidence from paleobiology with studies of model organisms. It embraces evidence of cell dynamics in a genomic framework. This frontier of progress has also attracted long overdue attention to the epistemological status of standard model organisms, and how well the phylogenetic positions of standard model species relate to the encompassing diversity (Jenner, Wills 2007; Jenner, 2014).

Here we see how the expansion of tree-thinking (O'Hara, 1988, 1997) continues to impact on the traditional roles of the stand-

ard supermodel organisms — e. g. fruit flies, *Aridodopsis*, *Mus musculus*, *Rattus norvegicus* — in modern genomics, cell biology and physiology (Jenner, 2014). Tree thinking reveals the established diversity of model species often misrepresents living complexity, as the phylogenetic position of a species has a strong bearing of the feasibility of comparisons, where investigators seek to understand aspects of organismal complexity. These demands challenge investigators to refine their choices of model species, and compile background natural knowledge of many more species, if they are to begin to tap into phylogenetic insights from comparative studies.

Moreover, and of key relevance to the Tentelic Thesis, model species maintained in laboratories are domesticated lineages that originated in wild species. Their modern status raises interesting questions about the provenance of laboratory models and founding diversity (Jenner, 2014; Alfred, Baldwin, 2015). Reverse ecology (Li et al., 2008) using genomic reconstructions can only go so far to elucidate the origins of model species.

Ideally, reconstructions of a model's evolutionary provenance need original tentelic information preserved in voucher specimens from founding populations. Do such specimens exist of the first rodents, nematodes, fruit flies, plants and microorganisms on which so much knowledge was published through the 20th century?

### **3. Emerging and future opportunities for Natural History**

#### **3.1. The New Natural History: molecular fingerprints of the evolving Earth**

The previous sections position us to examine the impacts of new advances and refined methods unfolding across the earth and life science, in all their parallel advances.

Here I focus on the significance of these fast-moving developments to the Tentelic Thesis, wherever information from natural science collections informs science. Thus, the maturation of biological methods, embodied in the resolution of Morgan's Deviation, have been matched by progress since the Plate Tectonics Revolution in refining the instrumentation of geochemistry and geophysics. They, collectively, continue to revolutionize our understanding of the Earth System.

Together, these advances in biology and geology realize the expanded scope of the Tentelic Thesis. Remarkable progress in the analytical sciences enables us to exploit molecular fingerprints of abiotic and biotic events to study the intricacies of Earth history since the Hadean. Science benefits from their collective epistemic powers in the complementary *Precision* and *Accuracy* undergirding analyses. The Principles of Molecular Specificity underpin widening applications of these methods across the sciences. This progress in instrumentation is key to understand how, in the 21st century, the natural sciences find themselves in the most remarkable circumstances. I argue we are seeing the growth and advance of a Molecular Natural History. In its expanding scope, the Tentelic Thesis undergirds the unfolding opportunities in Molecular Natural History (*aka* the New Natural History).

I scope out selected examples in the following paragraphs. Three radical discoveries stand out in emphasizing how genomics bolsters the new natural history. They all hinge on tentelic information preserved in natural science collections. One comprises geobiology, an interdisciplinary science in its right, and its scope continues to widen as it integrates biology and geology. Second, mineralogy is the science traditionally classified firmly within the abiotic domain of geochemistry. Yet, over the past decade, long

overdue discoveries of the biogenic origins of many of Earth's minerals demand that we reconsider the affinities of mineralogy within the earth and life sciences. This revolution has remarkable impacts on geochemistry.

Third, increasingly, refined analyses of fossils inform reconstructions of palaeoecological and phylogenetic affinities. These insights include the direct dating of fossils (e. g. Price et al., 2013; Trueman, 2013; Louys et al., 2016) and characterization of palaeoenvironments using fossil taphonomy (Trueman, 2013). More remarkably, the successes in genotyping ancient DNA (aDNA) sourced in near-fossils are especially impressive and illuminating, not least in specimens of Middle Pleistocene provenance (DeSalle et al., 2013). Recently celebrated breakthroughs have sequenced Middle Pleistocene *Homo*. The findings rewrite our understanding of our species' origins (Calloway, 2016; Meyer et al., 2016). These discoveries exemplify how the epistemic fecundity of specimens opens up unsuspected discoveries.

Continuing refinements in the precision and empirical reach of scientific instruments (especially mass spectrometry and molecular biology) are set to enhance and expand applications of "forensic" tools to probe specimens. Our ability to read previously hidden evidence in these libraries enables us to scrutinize more and more of the multifarious facets of Earth history. Improved accessibility of specimen-data is set to inform an unprecedented spectrum of research fields; moreover, integration of this evidence is pivotal to consolidate Earth System science. A fundamental commonality in their methodology unites all the different disciplines positioned to exploit these new tools. Grounded in the Tentelic Thesis, each investigation derives unique idiographic evidence preserved in the tissues and genomes of organisms, which are interpreted in their individual historical con-

texts. Realizing the increasingly integrated potentials of the analytical sciences makes it hard to identify any natural science specimen, which does not in some way give us some new insight into the natural world.

The fine precision is exemplified in laser probes — to analyse specimens directly: with minimal disruption to the integrity of preserved biological tissues, genomes and minerals (e.g. Copeland et al., 2011). Alongside uses of stable isotopes and other molecular tracers, we see the prominent example of these advances in the emerging "museomics revolution" enabled by 21st century genomics (Cotterill et al., 2014; Guschanski et al., 2014). The scope and precision of museomics continues to improve rapidly, delivering more and more data at exponentially decreasing costs; this progress hinges on the merging of bioinformatics with molecular analyses. Museomics exemplifies how the world's collections are opening up as massive libraries. We can anticipate the flow of discoveries from collections to increase, and to be consolidated, as integrated tentelic information interlinks research frontiers across Earth System science. Geoecodynamics is one pertinent example (cf. Cotterill, de Wit, 2011; Hoffmann et al., 2015; Cotterill, in prep.). Its opening up of the genomic record enables finer-scaled dating of landscape dynamics (in time and space). This resolution holds promising potential to inform more complete evolutionary reconstructions of landscapes and palaeoenvironments (Cotterill, in prep.).

### 3.2. A retrospective interpretation of progress in 20th century science

For convenience, this section provides an interim summary of my developing argument. I identified the significance of Morgan's Deviation to understand the remarkable progress unfolding across 21st century science, and how it hinges on the rise of mo-

lecular biology dominating the life sciences through the second half of the 20th century into the present. Its early successes motivated major efforts to develop nomothetic approaches in organismal biology, notably in ecology and paleobiology. The strengthening of geochemistry and geophysics (notably in geomagnetism) has paralleled these events in biology. Exemplified in geochronology, applications of these methods have had radical impacts across all the earth sciences, and equally in reconstructions of the history of Life. Underpinning conceptual and theoretical progress, the improved instrumentation in all these sciences proved essential to progress. Refined instrumentation underscores Horace Judson's emphasis in attributing the gist of the revolution in molecular biology to "molecular specificity".

The innovations in scientific instrumentation that transformed the sciences took off through World War 2 (Lee, 2014); we see the outcomes in imaging technology, space exploration, and hyper-precise characterization of materials. These abilities continue to hinge on marrying analogue instruments with digital technology for greater efficiency. This synergy has revolutionized the efficiency of information flow from subject to final target, such that today's scientists work more and more with digital data from initial data collection through analyses to formal publication.

Three examples stand out; ultracentrifugation, the Polymerase Chain Reaction (PCR) and the ability to label and track individual macromolecules with molecular probes (Johnson, 2007; Judson, 2013). The proliferation of 'omics founding so many new specialized disciplines in 21st century biology (Baker, 2013) reflects the major investments and rapid progress. Combining PCR, ngSQ methods and molecular probes — in attenuated microorganisms — to map neural connectomes exemplifies the undi-

minished importance of radical innovations in advancing biology (see Zador et al., 2012; Oyibo et. al., 2014). Mass spectrometry continues to have equally pervasive impacts across the earth and life sciences. I argue that the opening out and continued refinements of methods and discoveries grounded in the Principles of Specificity go a long way to explain the explosive growth in both biology and geology.

It is very clear how an immensely powerful armamentarium of analytical methods enable today's scientists to obtain unprecedented insights into natural phenomena. Their relevance to this paper centres on how they enable discoveries across the abiotic and biotic worlds to resolve remarkable details in complexity at the molecular level. The Critical Zone holds the myriad of opportunities for scientific exploration. Natural science collections preserve the most accessible assemblage of original research materials, which uniquely foster tentelic analyses in laboratories. Ironically, given how natural science collections are irreplaceable, the persisting Alexandrian Tragedy emphasizes how widespread ignorance threatens their collective future. The past and present status of natural history (Part I) underscores the gravity of this crisis.

### **3.3. Earth's Proteome: proxy of the evolving biogeochemistry of the Critical Zone**

"Biopolymers contain information about their evolution, structure, and function, and these three types of signals may interact in different ways, sometimes enhancing and in other cases interfering with each other. In a sense, whole biology for the past few decades has been dominated by the quest for ways to extract and analyze signals contained in molecular sequences. Genomics is a continuation of these efforts for our times, when complete genetic makeups of many species are known. At the same time,

genomics offers even more. Many times in this book, I will return to the argument that with complete genome sequences, we can answer many questions that we could not answer, or even could not think of asking, before. This is the new era in biology — the era of complete genomes”.

(Mushegian, 2007, p. 4)

Enzymes are the intricately folded protein chains (polypeptides) that catalyze biochemical reactions. Together with all structural proteins, this collective diversity comprises the Earth’s Proteome (Perez-Iratxeta et al., 2007), comprising a vast universe of functional complexity. Its greatest domain is contained among microbes. Only in a phylogenetic framework can we understand how the intricate and shared attributes comprising Earth’s proteome. Over the past decade, continuing progress in structural phylogenomics informs a timeline of enzyme evolution. Here, the estimated ages of protein folds that represent the “structural scaffolding” of biocatalytic mechanisms are central to inform the phylogenetic reconstruction of proteomic diversity (Caetano-Anollés et al., 2009, 2012).

The core narrative of this proteomic timeline unfolds as the natural history of biocatalysis: through all its major mechanistic steps in diversification throughout the planet’s Critical Zone. This diversity of protein folds and catalytic mechanisms maps out the spectrum of biogeochemical reactions as metabolic complexity diversified: ever since Life originated in the primordial chemistry of the young Earth, and established “Life’s nascent metabolic repertoire”; its inaugural events are exemplified in origins of redox metal binding domains that founded the young Tree of Life (Harel et al., 2014). This total diversity of enzymes and structural proteins of “Earth’s proteome” only assumes coherence when cast into a phylogenomic framework. Only then can we map out the protein universe, sampling the living

expanses of extant biodiversity back to the events that inaugurated Life in the prebiotic world (Caetano-Anollés et al., 2009, 2012; Caetano-Anollés, 2016).

The dimensions of the “Earth’s Proteome”, as the global inventory of all the proteins so far known to proteomics, holds intriguing lessons. Firstly, it reveals science has already discovered the greater majority of all proteins. Second, this knowledge testifies to the laudable progress by genomics (represented here by proteomics) in mapping out biotic and biochemical complexity at its very core. The third, and most powerful attribute, lies in the illuminating contributions to geobiology, and all sciences researching the biogeochemistry of the Critical Zone. Earth’s Proteome provides us with a most useful index — in the currency of biogeochemical reactions. This proxy gives us a narrative of the evolutionary events that impacted on the Critical Zone.

In its global context and applications, Earth’s Proteome hints at future potential for other sciences, as the latter integrate with genomics; we can expect to see more and more genomic data flooding into interdisciplinary research arenas. These explorations have already begun. The Microbial Earth Project (Microbial..., 2016) is generating a comprehensive genomic catalogue of all known Archaea and Eubacteria, while the Earth Microbiome Project (Earth..., 2011) uses metagenomics to analyse microbial diversity at a global scale. Furthermore, the practicalities of using Single-cell genomics can map out patterns representing biotic processes within the Critical Zone with impressive precision. As it proceeds to complete a comprehensive sampling of all major branches of the Tree of Life, this will provide “...for the first time a global view of the evolutionary forces that have shaped Life on Earth” (Rinke et al., 2013). The insights resolving

key events in Earth history are nothing less than remarkable. For example, a recent study (Rothman et al., 2014) has attributed expansion of acetoclastic *Methanosarcina* to a single horizontal gene transfer in the Late Permian, which caused biogeochemical disruption, together with massive volcanism that caused the Permo-Triassic extinction. This serves as an apt example of the resolution obtained from phylogenetic and ancestral trait analysis, which applied a molecular clock to calibrate rRNA genes to resolve the timing of horizontal gene transfer that culminated in massive methane upsurge. At the molecular scale, the transposon event that reshaped the proteome of *Methanosarcina* had sweeping impacts across the Earth System.

An index of progress toward obtaining this global view of evolutionary history is provided by a Time Tree that reconstructs the origins of 3249 microbial gene families. This timeline is rooted in the early Archaean. It highlights how the tempo and mode of biochemical innovation entailed significant pulses, notably over the Archaean and Proterozoic (David. Alm, 2011; Caetano-Anollés et al., 2012). And a subsequent study has demonstrated that the timing of inaugural events in protein innovation provide strong support for the coevolution of biochemical and geochemical complexity. These innovations are illustrated by the timings for the first appearance of aerobic metabolism in the Proterozoic oceans (Kim, Caetano-Anollés, 2012; Saito, 2012). These discoveries endorse the argument of Boussau and Gouy (2012), in proposing a focused inventory of the genomic record to discover and characterize the inaugural, ancient events in biotic evolution, each of which interfaced with major events in the geological and climatic evolution of the early Earth.

We can also examine the broader and deeper dimensions of the biochemical uni-

verse, in all its proteomic diversity by extending the argument of Gould (1989) and Pavlinov (2011). We can evaluate the evolution of protein “morphospace” throughout the Critical Zone to ask fundamental questions about its structure. Pertinently, is proteomic morphospace continuous or discretely structured? We first need the robust primary idiographic data to inform searches for the ultimate causes and responding mechanisms that have directed, contained, and shaped proteome evolution. Inaugurated in pioneering phylogenomic research (cited above), this strategy propels proteomics into an Earth System framework. We are challenged to explain the interplay between the ecospace and geospace of the Critical Zone in the currency of biogeochemical evolution. This quest brings proteomics into a tight juxtaposition with the molecular intricacies of mineral evolution (see below).

I predict exciting times ahead as the integration of structural biology and phylogenomics (Mushegian, 2007; Caetano-Anollés et al., 2009; Caetano-Anollés, 2016) interfaces with not only environmental microbiology and metagenomics (Falkowski et al., 2008; NRC, 2009; Doolittle, Zhaxybayeva, 2010) but especially mineral evolution (Hazen et al., 2008; Hazen, Ferry, 2010; Hazen, Papineau, 2012; Grosch, Hazen, 2015). Representative inventories of Earth’s Proteome are challenged to frame surveys in geomorphological and geological maps of the diversity of landforms and Critical Zone processes.

We can see the remarkable potential opening up across this entire field to survey the functional diversity of the Critical Zone across all scales — from genome to ecosystem. Crucially, we will need to evaluate new proteomic and biochemical data using tentelic collections of microbes *and their microhabitats (both biotic hosts and minerals)*. Here, surely, the consortium of

sciences mapping metagenomes and proteomes is challenged to maintain tentelic repositories of microbes and samples, especially those obtained in costly surveys of extremophiles? Future scientists will likely apply more refined molecular methods in unprecedented advances in proteomic evolution. Structured by Earth history, they will depend on tentelic repositories of proteomes as the essential sources of evidence to evaluate, and either refute, or refine, pioneering discoveries.

### 3.4. Mineral evolution

In their consolidation since the 1950s, geochemistry and petrology qualified as analytically rigorous sciences. Implicit in their practices, both sciences are rooted firmly in the physical sciences, and especially in inorganic and physical chemistry (Johnson et al. 2013; Walker 2013). These interrelated disciplines do indeed hold strong nomothetic credentials. Just acknowledge the tight causal relationships between pressure, temperature and depth that determine metamorphic grades, and the remarkably interlinking of geochemical patterns and processes so tightly into the consilience of the kinematic theories undergirding plate tectonics (see Frisch et al., 2010 and Frankel, 2012a–d for an overview and historical context, respectively); and we can equally invoke the fascinating applications of radioactive and stable isotopes to fingerprint the affinities and evolution of minerals and rocks (Allègre, 2008). Exemplified in development of a temperature probe of Earth's temperature (Hoffmann, 2012), these advances hinge on advances in instrumentation, which enabled precise measurements (Johnston et al., 2013) to discover and correlate palaeoenvironmental events. We see analogous breakthroughs in the refined applications of cosmogenic isotopes to date landforms (Granger et al., 2013).

The realisation that the diversity of Earth's mineralogy is: (1) the outcome of evolutionary processes, and (2) that organisms have shaped mineralogenesis in increasingly dominant roles since the Archaean is, to state it mildly, radical news. Over the past decade, the discoveries have flowed out in a distinctly silent revolution in a series of papers (Hazen et al., 2008, 2009, 2012, 2013a,b, 2014, 2015a,b; Hazen, 2010, 2012; Hazen, Ferry, 2010; Hazen, Papineau, 2012; Grew, Hazen, 2014; Grosch, Hazen, 2015). It shakes geochemistry, petrology — and thus the all “hard-rock sciences” — to the inorganic roots of their nomothetic credentials.

The stark lesson is that historical contingency has shaped Earth's mineralogy. These origins and dimensions of Earth's mineral diversity can only be understood in the light of evolutionary history. Major transitions in the evolving Earth System can be read as a sequence of unique thresholds that have reshaped mineral diversity since the Hadean. Since the Archaean, the role of organisms has increased as the dominant agents of mineral formation, and driven the Earth System across each threshold, for example the switch from a reducing to an oxidizing atmosphere. As distinct events, each of these thresholds holds central causal relevance in the evolution of the Earth System.

So we might empathize with those earth scientists surprised, if not perplexed, at facing a revolution from within; one, which, not yet a decade old, positions geochemistry and petrology to overlap with biology. In realigning these sciences, this revolution is grounded firmly in the life sciences. It extends the principles of natural history. Most importantly, the “New Mineralogy” repositions the earth sciences firmly within the fold of geobiology. Just consider the now altered situation that petrology faces, given its mandate that it “...is restricted to the study of the



processes that cause the differentiation of the terrestrial planets from which we have samples” (Walker, 2013, p. 2).

The encompassing argument of this paper reveals that mineral collections attain a whole new status as tentelic sources for evolutionary research and Earth System science. The modern geochemist holding strong affiliations with the physical sciences faculty has to consider museums with due respect; this is nothing less than remarkable considering how it appears that mainstream geochemistry has seldom, if ever, considered including biology at the core of its curriculum.

It is interesting to see which of the world’s universities will lead the way forward to embrace and extend these frontiers of natural history. Which university will reshape its curricula and reach out to study collections of minerals and other specimens? The origins of each and every mineral formation are embedded in contingencies of Earth history. They are each unique. The origins of these minerals are all the more likely to have been causally interlinked with biospheric processes in the Critical Zone.

The Tentelic Thesis is especially relevant in mineralogical studies reliant on costly analyses (using mass spectrometry and other methods) to characterize minerals; the responsible scientific investigator is beholden to preserve tentelic references of mineral subjects for future independent referrals. Meeting this responsibility can only aid and abet calibrations of new methods in the future. This significance of tentelism will increase in 21st century science, as the expanding quests to explain evolutionary phenomena in the evolving Critical Zone apply molecular-focused methods (e. g. AMS, ngSQ) in analyses in researching the evidence to explain the evolutionary origins of phenomena.

The swelling revolution in our understanding of the origins and complexity of

mineral diversity meshes with studies of the proteomic, cellular and ecological complexity of microbes, and all other organisms; at their very core, investigations of mineral diversity in space, time and form overlap broadly with those that structure the life sciences. It is all natural history.

All these exciting new approaches consolidate the integration of biology and geology in the framework of Earth System science. Together, they underscore why the complexity being revealed in the “New” mineralogy only makes sense when classified into a historical framework. The mineral diversity of our planet has evolved through a recognizable sequence of episodes. Organisms have exercised an increasingly dominant role in shaping mineral diversity. Moreover, in an even broader context, all these new developments mesh geobiology ever closer with molecular biology, as the challenges of evolutionary questions propel molecular biology (in all its new subdisciplinary specialties, Baker, 2013) firmly into the bosom of natural history.

### 3.5. Molecular natural history: toward a geobiotic record of Earth history

“To place all the scattered pages of Earth history in their proper chronological order is by no means an easy task”.

(Holmes, 1965, p. 148)

“It is now clear that the stratigraphic record is more than just incomplete. To extend Ager’s (1993a,b) famous thought: there are gaps within the gaps, and the record is permeated with them, at every scale. The frozen accidents that the gaps enclose can still tell us a great deal, but only if we get the time scale right”.

(Miall, 2015a, p. 31)

We have seen how the scientific histories embodied in Morgan’s Deviation and the Eclipse of History hold instructive lessons. They highlight the eventful upheav-

als in the passage of natural history since the 19th century. They further emphasize how advances in scientific instrumentalism facilitate and enable unexpected studies in natural history. By opening up new research opportunities across collections, I argue the armamentarium of the 21st century sciences is reincarnating natural history; albeit the science is now dressed up in the uniform of molecular evolution. The origins and scope of molecular natural history are best understood as the graduations of twinned siblings, which until recently grew up in isolation. One twin is molecular biology. Geochemistry is the other.

The state of genomics and proteomics in modern biology testifies to the vibrant growth of molecular natural history. These sciences can only advance by extending the principles of the classical science of natural history in their quest to decipher the historical origins of biomolecules. Today, the explosive growth that propelled molecular biology forward, beyond Morgan's Deviation, focuses increasingly on applying molecular solutions to problems in organismal biology. These applications are by no means restricted to solving the riddles of how animals and plants develop.

Here it is instructive to compare the epistemological scope of different sciences. Studies of animal behaviour, for example, focus on researching organisms, but explanations extend to explain how impacts of behavioural diversity have shaped emergent attributes of ecosystems over time; we see in the accumulation of nutrients into tertiary consumers, how countless predation events culminate in biological magnification within food webs. The explanatory scope of some sciences, however, penetrates deeper and further, where their threads of causal explanation span unprecedented expanses of phenomena.

This greater reach enables such sciences to explore vertically upward, and/or downward, in mapping out the complexities of the natural world. An excellent example is the ability of molecular analyses to map out the impacts of the expansion of acetoclastic *Methanosarcina* in the Permo-Triassic extinction (Rothman et al., 2014). The resolving spans of such scientific explanations extend across nested levels of hierarchical organization: from genomes and minerals, through cells and organisms, to solve problems in the structure and origins of ecosystems and landscapes at the global scale. Such a science exhibits expanded **epistemic scope**. Equally, structured in applications of the Tentelic Thesis, significant discoveries and explanations of such sciences illustrate the impacts of the mechanism of high **epistemic fecundity**: major and/or unanticipated discoveries motivate and lead scientists to ask unanticipated questions (see below).

Genomics and geochemistry exemplify sciences with a broad epistemic scope (and often high epistemic fecundity). Geochemistry can exploit fingerprints of minerals to track events within and across individuated units of continental and oceanic lithosphere, and this approach can resolve ancient events in their revealing details. This analytical resolution of geochemistry extends into ecosystems to map out trophic pathways. In genomics, the threads of explanation extend from within cells outward through the intricacies of organisms to populations, species and biota. Its resolution does not stop there. It extends deep into geological history, as we see in how genomic evidence estimates the timings and locations of events within ecosystems. These applications rely on molecular clocks to date events in the genomic record (Cotterill, de Wit, 2011; DeSalle et al., 2013). Here, we can extend insights revealed by these quantified events in geocodynam-

ics to explicate the tempo and mode of other earth processes at larger scales of organization (Cotterill, in prep).

Separately, and in combination, the expanded epistemic scope of geochemistry and genomics can map out details in earth history at fine precision; with insights extending outwards across the macroscale of the evolving Earth System. The discoveries they enable blur the traditional boundaries demarcating the earth and life sciences. We can track fingerprints of target molecules to map out and resolve chains of causal explanation that extend upward and outward to explicate the events, processes and patterns that played out in magma, sediments, and/or in ecosystems. Albeit, the resolution of the genomic record is restricted to zones where Life has always persisted, and preserved its genomic record in DNA and RNA.

These reveal new challenges across Earth System science; they include the challenges of how to integrate our knowledge of these two great evolutionary systems that present in such a wealth of abiotic and biotic evidence. Their integration can only reinforce our understanding. This follows especially where the consilience, conferred by combining separate lines of evidence, explicates how shared links among scattered impacts point to a singular cause. The pairing of molecular clocks with rock clocks holds exciting opportunities to obtain these reciprocal insights. This is where there is vast potential to refine the precision and resolution of molecular clocks, by tuning biochronological dates against precisely constrained geological events dated with geochronological tools (cf. Benton, 2015; Benton et al., 2015). These opportunities raise interesting questions as to what new proxies — applying such integrated methods — await to be discovered and developed in natural science collections?

This is also the appropriate place in this essay to highlight the fascinating patterns of congruence, which interlink the tempo and mode of events recovered across the geological and biological records of planetary evolution. These stratigraphic, geomorphological and palaeoclimatic records, and also what is currently known of mineral evolution, correlate in their principal dynamics. The overall congruence in these abiotic records reveal even broader synchrony with the major trends preserved in the fossil and genomic records of biotic evolution. This congruence is robust. Its signals stand out despite respective gaps and patchiness in coverage of the different records. Significantly, the physical domain of their correlation is congruent with the Critical Zone. The strongest shared signals point to impacts of rarer events of higher magnitude in their impacts on the Critical Zone. Each represents the wide-acting impacts of comparatively rare volcanic eruptions, and major climatic and tectonic events. These mega-impacts have controlled abiotic and biotic processes at macroscales across the Critical Zone and Earth System. Catastrophes hit Earth rarely, but they hit hard.

It follows that making sense of the underlying causes of the common events and patterns, represented in these patterns of earth history, will consolidate the integration of the earth and life sciences. Nevertheless, to date, the pertinent research efforts have largely progressed in parallel; cross-pollination is the exception. This state of affairs reveals the rich opportunities to synthesize evidence from the earth sciences (geomorphology, and sedimentary and tectonic geology) with the life sciences (landscape ecology, palaeoecology and paleobiology). Arguably, genomic evidence strengthens reconstructions, where geocodynamics obtains the high fidelity

resolution to link biotic events with abiotic records (Cotterill, in prep).

The intensively studied histories of sedimentary systems hold poignant lessons, where we seek to understand the tempo and mode of Earth history. The nature of the stratigraphical record exemplifies a pattern dominated by large gaps over the passage of time, which are interleaved by rock formations formed during shorter, rarer, formative events. Continuity in the rock record is the exception. Studied in either exposure or core, any layer cake of sediments is mostly empty of evidence: being full of gaps punctuated by rare deposition events fortuitously preserved (Miall, 2013, 2014, 2015a,b). To quote the late Derek Ager, this pattern of the rock record aptly fits the alternative description “of a net as a lot of holes tied together with string. The stratigraphical record is a lot of holes tied together with sediment”. Thus “*the sedimentary record at any one place on earth is nothing more than a tiny fragmentary record of vast periods of earth history*” (Ager, 1993a, p. 53).

Moreover, the universal pattern of “frozen accidents” that shaped the mostly empty Rock Record fits well with the argument by Brunsten (1993, 1996) that formative events are relatively rare in geomorphic systems. It is the rarer, higher energy events that can overwhelm the thresholds of resistance to change in landscapes. Rare, higher magnitude events have done most of the work of reshaping landscapes over evolutionary time scales, reshaping topography and earth surface regimes (Brunsten, 1993, 1996, 2001). Even where geologists cannot find material evidence of their impacts on the Critical Zone, the genomic record can preserve exemplary clues of impacts, because DNA has tracked the turnovers of biodiversity over evolutionary timescales (Cotterill, de Wit, 2011).

The congruence we see emerging across all these bodies of evidence in stratigraphy, radiometric geochronology, geomorphology, macroevolution, palaeoecology, paleobiology and geocodynamics are unlikely to reflect spurious signals. Each record independently testifies to the shared impacts of singular formative events: each of their impacts overlapped at a particular time and places in Earth’s history (Cotterill, in prep.). In this context, the “Sloshing Bucket Hypothesis” accounting for major biotic turnovers — punctuations of species’ stasis — in the fossil record, through geological time, also invokes large scale environmental changes as their ultimate drivers; for these hard-hitting events that modified the biosphere reveal their tendency to cluster at regional, continental and global scales. The Sloshing Bucket Hypothesis provides a unifying explanation for the major macroevolutionary patterns, which focus intensive research in paleobiology (Eldredge, 2003, 2008, 2015a,b).

It follows that it will prove rewarding to correlate unique events in the rock record against those revealed in corresponding records of Earth history, especially the biological evidence. Thus the evidence represented in individual strata (facies), surfaces — and thus events preserved in the exposures, or cores, or landscapes studied by earth scientists can also be read in corresponding suites of tentelic information in preserved biological specimens. Opportunities opening up in the new disciplines of biogeomorphology and geobiology extend to the repositories of tentelic evidence preserved in collections; here, specimens of fossils and extant biodiversity hold vast potential to fingerprint individual formative events. We should seriously explore the feasibility of collating consilient databases that integrate all available evidence. Ideally, the synthesis for a

discrete span of geological time will build on the scaffolding of calibrations represented as individual events represented in the discrete lithological units of the rock record. Where it proves possible to integrate geobiological evidence into such a narrative, key facets of evidence will explain salient details of events that occurred during great lapses in sedimentation (so escaping preservation in the rock record).

The nature of surviving rock formations raises the interesting hypothesis that their long-lived surfaces comprised long-lasting Earth surfaces, each of which fostered geomorphological regimes, inclusive of their biodiversity. This leads to the possibility that some of these surfaces may preserve geobiotic signatures, which we can read from representative rock and sediment specimens using stable isotopes? Some of these younger, anaerobic units in the rock record might preserve semi-fossils with readable ancient DNA?

And indeed they do: palaeolimnological studies of aDNA in Late Quaternary lake sediments validate this method, which can resolve events within  $10^4$  years (Epp et al., 2010, 2015; Boessenkool et al., 2014; Stager et al., 2015). These interrelated records of the evolving Earth System have a powerful relevance to the core topics of this paper, and they are no less fundamental to the central challenges faced by stratigraphers. Their potential embraces and extends the argument of Miall (2015a,b). Reconstructing the tempo and mode of Earth history demands robust consilient evidence. It is by no means just a matter of getting the scale right in reading the spectrum of events that shaped the rock record.

All these collective opportunities hold a keystone, epistemic role in the quest to understand the shared signals exhibited in the tempo and mode of records of Earth history:

preserved in patterns of biodiversity dynamics (fossils and genomes), land surfaces (geomorphic), and rock formations. They emphasize why we should not hold back from the search for interdisciplinary solutions in science. This emerging research arena equally illustrates the widening embrace of the Tentelic Thesis, wherever the wealth of specimens can resolve the spectrum of signals in diverse arrays of evidence of Earth history.

And, these opportunities highlight the procreative metaphor that compares the stratigraphical record to music: "...the intervals between the notes are every bit as important as the notes themselves, so the bedding planes are as important as the beds" (Ager, 1993a, p. 53). If they have survived in rock formations that should come to attain all the status of *lagerstätten* (cf. Nudds, Seldon, 2008; Seldon, Nudds, 2012), geobiotic proxies could revolutionize our ability to read the tempo and mode of the evolving planet; and so we will come to see details in its history in a whole new light.

Including stable isotopes, prospective applications of geobiotic proxies hinge on the genomic record, which opens interesting opportunities (Johnson, 2007; Cotterill, de Wit, 2011; Cotterill, in prep) to close gaps in sedimentary and geomorphic records. It exploits the unbroken chains of evidence accumulated in the genome. The latter's integrity is enabled by the uninterrupted recording by the processes of genetic inheritance through generations; these accumulated global repertoires of DNA in genomes — the "Delphic Boats" (Danchin, 2002) — preserve a unique record. Pioneering progress in reading the genomic record reveals that we can indeed read details of landscape history hiding among the vast gaps of the rock record (albeit for younger events since the Late Mesozoic, see Cotterill, de Wit, 2011; Hoffmann et al., 2015; Cotterill, in prep.).

Together, all these insights point to the feasibility of combining complementary bodies of evidence, representing shared episodes of Earth history: in fossils, genomes, landforms and palaeoclimates. This is where I argue (Cotterill, in prep) that resolving the currently obscured linkages across climatic, fossil, genomic, geological and geomorphological records will integrate evidence for events and their causal mechanisms. Consilient evidence will strengthen the current state of palaeoenvironmental reconstructions, where, currently, ubiquitous gaps and patchy coverage of single records hinder deeper, synthetic understanding of the hidden details of Earth history. I argue that this interdisciplinary strategy holds interesting potential to reveal the wider spheres of causal influences — in the currencies of their origins and mechanisms.

In summary, where historical records can be integrated in all their consilient resolution, our success in synthesizing their complementary narratives will provide Earth System science with a singular, multifaceted geobiotic record of Earth history. The Critical Zone preserves the richest repositories of evidence. And this is where natural science collections are uniquely positioned to aid and abet researchers endeavouring to decipher a consilient narrative. The shared challenges centre on decoding universal aetiological explanations: revealing the singular causes interrelating respective patterns in the different records. Arguably, resolution of these narratives will reveal how the tempo and mode of the evolutionary dynamics played out across the Critical Zone.

Provided it embraces natural history, we can be confident that 21st century science — in its remarkably advanced instrumentation — holds the tools to resolve an integrated classification of all the events encoded in the bodies of stratigraphic, geomorphic, palaeoclimatic, biotic and genomic evidence. This

emerging research frontier, focusing on the evolving Critical Zone, will shed new light on our understanding of the tempo and mode of mineral evolution. Consilience will hold a keystone role in structuring this robust narrative.

Where science succeeds in deciphering these consilient narratives, we can be justly proud in obtaining an unprecedented geobiological resolution of Earth history. We will have made constructive sense of many scattered pages of fragmentary evidence. Empowered by refined instrumentation, natural science collections are uniquely positioned to undergird these interdisciplinary quests for geobiotic narrative of Earth history.

#### 4. Conclusions

Darwin's "Worm Book" is too often dismissed as the quaint nature notes of an aged sage. Nothing could be further from the truth. An enlightened interpretation positions *The Formation of Vegetable Mould through the action of worms* (Darwin, 1881) as a mature exposition of how so many contingent, microscale events can accumulate to shape the macroscale patterns of the Critical Zone; thus, published decades ahead of its time, this monograph on the behaviour and ecology of the Oligochaeta ranks as the definitive statement establishing bioturbation. The tripartite of bioturbation, process and form drive the dynamics of evolving continental surfaces (cf. Johnson, 2002). The significance of this founding treatise of geobiology is even greater, for Darwin celebrates the status of the Enlightenment by the late 1800s.

Darwin's unifying lesson highlights the keystone position natural history holds in the sciences; above all — in over arching tribute to earthworms' profound, macroscale impacts — the work celebrates the discovery of Deep Time; this revolution has proved eminently foundational; such that, well over a century

since the concept matured, it undergirds all the evolutionary sciences. Manifestly, clear-cut logic dictates why Deep Time magnifies the keystone role of natural history in any scientific characterization of evolutionary phenomena. Yet, in the decisive decades since 1881, in contrast to its grand triumph in the Enlightenment, natural history experienced decidedly shifting fortunes. Notwithstanding all their outstanding achievements, the voyage of the sciences through the 20th century carried natural history as a barely tolerated stowaway. Finally, emerging from its prolonged metamorphosis, the stamp of natural history illuminates a spectrum of cutting-edge discoveries. Building on the foundations established by the Enlightenment pioneers, 21st century opportunities and developments consolidate this core science.

In all its impacts and outcomes across a spectrum of scales and form, historical contingency has set pervasive controls on the tempo and mode of Earth history. Ever improving tools enable us to make sense of how this complexity has evolved from the molecular scale through to the diversities and historical fates of organisms and landforms; and we can map out and classify each macroscale process, dominating the solid, liquid and gaseous spheres, in the context of Earth's history. The prism of historical contingency has shaped this spectrum of evolutionary outcomes. It equally structures how science works at the research frontier challenging a multitude of disciplines. All their interpretations continue to build on the Enlightenment's pioneering discoveries that founded biology and geology; and we rely on the Individuality Thesis and Darwin's Law for the universal ontology to identify and classify any evolving pattern or process. The Tentelic Thesis enables, and supports, the epistemology of this entire research frontier. Tentelism prescribes why each research domain collects

and preserves vouchers of the multitude of singular observations.

The history and current status of science testifies to how dogmatic paradigms too often suppress innovative questions and research; this is especially where inertia quashes opportunities and initiatives. The ivory archipelago of academia (Wilson, 2007) dominates the teaching and funding of science. The majority of investigations continue to be framed within scientific disciplines, administered and directed from within each of these introspective silos curating traditional disciplines. In this context, the peerless *epistemological* values of natural science specimens remain poorly appreciated, especially overarching roles and relevance. The credentials of the Tentelic Thesis are very poorly recognized, let alone taught. The time is long overdue to fix this disturbing deficiency. Obviously, pedagogy is the way forward. Museums are challenged to lead efforts, and broadcast why it is that tentelism is the primary *raison d'être* for why scientists collect and preserve specimens, and seek out new insights.

Contrary to naive belief, and how whiggish histories of science position the Voyages of Discovery as events in the past (central in the emergence of biology during the 19th century), our explorations of the biosphere remain very inadequate. The Wallacean Shortfall underscores big gaps in biodiversity maps (Lomolino, 2004). Ongoing inventories continue on land and sea (Donoghue, Alverson, 2000), and in the air (Womack et al., 2010; Smith, 2013). At least one quarter of Earth's minerals are undiscovered (Hazen et al., 2015b). A wealth of discoveries continues to pour into museums, at a time when scientific instrumentation is superbly strengthened to explore the complexity of the natural world from genomes, cells, and mineral grains, outward across the Critical Zone.

This knowledge deficit, together with the challenges and opportunities, endorse earth and life scientists to work more closely together. Today's sciences are uniquely empowered to work in partnerships: in affiliations the pioneering founders of these disciplines could never have anticipated. The challenges of Earth System science and the complexities of geobiology make immanent changes hard to avoid. Given the latter's demands, the significance of natural science collections has never ranked higher. This is where specimens hold pivotal roles in all the ways whereby epistemic fecundity and epistemic fidelity underpin scientific discoveries. Here, especially, precise determinations of biochemicals and geochemicals — refining Principles of Specificity — expand the epistemic scope for new, surprising discoveries.

These epistemological realities and opportunities underscore why the state of 21st century science — its refined instrumentation especially — broadens the scope and deepens the significance of the Tentelic Thesis. I have argued that refinements of molecular methods (demonstrated and potential) rejuvenate natural history, and unify the natural sciences. These developments, in turn, elevate the values and relevance of natural science collections in research. In this overarching role, as the core science in 21st century science, natural history enables any research activity reliant on collections. In its expanding epistemic scope, natural history can integrate and classify a diversity of historical data: flowing from specimens into the many different specialist disciplines. This potential is exemplified in the emerging opportunities to build a consilient evolutionary narrative of the Critical Zone; in which natural history integrates geological and biological records preserved in extinct and extant biodiversity, palaeoclimates, landscapes and the rock record.

Among all mechanisms of discovery, history reveals how the two overlapping operations of epistemic fecundity and interdisciplinary integration advance science. Epistemic fecundity flourishes in those unique circumstances of academic environments that foster the asking of new, unanticipated questions. Invariably, established scientists had never anticipated the subjects nor bearing of these new questions. Their impacts act via positive feedbacks, as new insights open out into larger perspectives, which in turn reshape previous frontiers of ignorance. Science is then able to see further, deeper, and can often identify entirely new research challenges.

A cluster of fruitful scientific questions can catalyse pulses of unanticipated growth, which can be sufficient to attract and establish a new discipline in its own right. Here, epistemic fecundity dovetails with interdisciplinary integration; our abilities to identify new questions often occur, in the first place, in the unanticipated meeting of scientists from very different backgrounds. Analogously, the integration of two or more disciplines can engender the most unexpected outcomes, when they consolidate remotely isolated ideas and methods.

Natural science collections are uniquely suited to foster such unanticipated meetings between scientists of very different backgrounds. And this is where the mechanisms of epistemic fecundity and integration are already expanding the scope and significance of the Tentelic Thesis; under the aegis of Earth System science, widening integration of biology and geology empowers new insights: identifying new questions poised along previously unrecognized frontiers of discovery. It is instructive to examine these two interlinked mechanisms in more detail.

Clearly, epistemic fecundity and integration operate in mutual tandem. Prominent episodes in the history of science, exempli-



fied in geophysics and molecular biology, demonstrate why the integration of formerly isolated sciences is a powerful epistemological mechanism. Emboldened by entirely new questions, the histories of both these sciences reveal "...research at its best is the finding of answers about the world that have not previously been asked." (Maddox, 2013, p. xxvi). Such successes emphasize how a wealth of serendipitous discoveries grow and bear fruit along new frontiers of discovery. In this paper, I have argued that the new (and refined) analytical methods revitalizing natural history enable science to ask entirely new questions about the evolving Earth System.

Underpinned by tentelic veracity, structured by taxonomy, a universal methodology enables and empowers natural history. Married with the refined instrumental precision of the analytical sciences, the epistemic scope of its discoveries are enabled by the unique ability of this methodology to classify facets of historical evidence. We have no competing methodology able to inform and guide research within, and across, the many traditionally isolated disciplines informing Earth System science (Cotterill, in prep). The origin of life, geocodynamics, and the "New Mineralogy" are three of the exciting research arenas opening up across geobiology. The expansion of geobiology testifies to how integration of disciplines identifies new research opportunities. We can anticipate yet more unanticipated insights, as refined methods allow new ways to study old specimens. As libraries preserving inestimable epistemic fecundity, the world's irreplaceable natural science collections preserve a wealth of opportunities. Never before have collections been so empowered to engender a new Age of Discoveries.

The fundamental roles of type specimens in taxonomy ranks as perhaps the best known attribute of collections: in classifying and

naming biological species, minerals and molecules. As the epistemic fecundity and scope of collections increases, taxonomies structure the expanding tentelic loom — the scientela — wherever we apply knowledge. More than ever before, the earth and life scientists need the theories, methodologies, and above all the data, structured by natural history to make sense of the historical events that shaped the Earth. This applies particularly to attempts to model the complex dynamics of the evolving Earth. The operational rule that "all models are wrong but some are useful" (Box, 1976) underscores why we need robust, representative idiographic knowledge to inform, and especially validate, any model we build in a supercomputer to try and approximate natural complexity. And if it is to begin to try and approximate reality, any such model has to be framed in not only phylogenetic history but palaeoenvironmental history.

Those researchers and institutions that embrace and extend the expanding epistemic scope of natural history stand to reap rich dividends in discoveries, enabled by integrated research strategies. There is convincing evidence that geobiology, biogeomorphology and geocodynamics hold remarkable opportunities: not least where evolutionary insights inform biotechnology and other applied sciences. Burgeoning discoveries being enabled by the armamentarium of modern science demonstrate the new insights flowing from the genomic and isotopic evidence preserved in tentelic specimens in all their unprecedented details.

We can only guess at what future explorations will reveal in the way of new insights and applications. We can expect unexpected partnerships and collaborations to explore collections of organisms and minerals with yet more new methods. Framed in the vast scope and potential of Earth System exploration, and founded on natural science collec-

tions, the revival of natural history challenges orthodox academia at very roots.

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