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Main Article:

Scientific Journals as Fossil Traces of Sweeping Change in the Structure and Practice of Modern Geology

Sarah E. Fratesi
Department of Geology, University of South Florida, 4202 East Fowler Avenue, Tampa, Florida, 33620, USA
bethfratesi@gmail.com

H. L. Vacher
Department of Geology, University of South Florida, 4202 East Fowler Avenue, Tampa, Florida, 33620, USA
vacher@cas.usf.edu

Abstract

In our attempts to track changes in geological practice over time and to isolate the source of these changes, we have found that they are largely connected with the germination of new geologic subdisciplines. We use keyword and title data from articles in 68 geology journals to track the changes in influence of each subdiscipline on geology over all. Geological research has shifted emphasis over the study period, moving away from economic geology and petroleum geology, towards physics- and chemistry-based topics. The Apollo lunar landings had as much influence on the topics and practice of geological research as the much-cited plate-tectonics revolution. These results reflect the barely-tangible effects of the changes in vocabulary and habit of thought that have pervaded the substance of geology. Geological literature has increased in volume and specialization, resulting in a highly fragmentary literature. However, we infer that "big science," characterized by large amounts of funding, collaboration, and large logistical investments, makes use of this specialization and turns "twigging" into a phenomenon that enhances, rather than inhibits, the enterprise of research.

Keywords: science studies; big science; twigging; lunar exploration

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1. Introduction

Geological research has shifted emphasis during the twentieth century. Observation-rich practices centered on a direct interaction between geologists and outcrops of rocks have given way to theory-dense studies based upon laboratory analyses and remotely gathered information. Acquiring a clear picture of the nature of these changes is difficult, however. Personal accounts are colored by attitude and by the decades that have passed since geology existed in a noticeably different state. Finding the exact cause for major changes in geological practice is just as problematic. Can we credit technology for an increased capacity for observation and cognition? Or do we blame it, as some do, for the loss of immediate contact between man and nature, one of the values that geologists pride themselves on? Does society need something different from geologists than it did before? Or has the science matured to a state wherein different requirements exist for geological proof?

There is a starting point for such inquiries: how geology changed in the twentieth century during the revolution of plate tectonics. This paradigm shift is an example given by countless scientific philosophers and information scientists of the potential for change in a science (Frankel, 1978; Kuhn, 1962; Laudan, 1978; Le Grand, 1988; Ruse, 1978; Solomon, 1992). But, in a pragmatic sense, the impact of plate-tectonics theory may be only moderate in comparison to the effects of technological advances, cultural and economic shifts, and even the changes in the culture of academic science on the practice and philosophy of geology itself.

This article is part of a larger study that asks the question: How has geology changed substantively in the past half-century? Has the nature of geological inquiry changed, or have we simply traded one set of tools for another? In this study, we look for quantifiable evidence of change within the enormous geological literature of the twentieth century.

In geology, a *trace fossil* is a rock containing footprints or tracks made by an animal. A trace fossil can be anything that an animal left behind to indicate its existence, except for the body of the animal itself. In this study, we have taken the scientific literature to be trace fossils of the practice of research geologists. We acknowledge that a scientific article may not record the logic of discovery involved in its creation. However, a journal article is usually the only real, enduring manifestation of a piece of scientific activity. The journal article is meant to be a part of the fossil record. And so shall we treat it.

Longitudinal studies of articles in a particular journal or set of journals are often used as records for the study of changes in the science itself (for example, Battalio, 1998; Bazerman, 1984). But the scientific literature is a complex and growing network. As any science develops and becomes more complex, its literature expands and branches off into separate subdisciplines. This phenomenon spawns changes in the economics of scientific publications, and it even changes the science itself. It may also highlight or obscure real longitudinal trends in science over time as articles on specific topics are funneled off into specialized subdiscipline journals.

In this study, we explore the topics covered in geology journals. We recognize three levels of journals:

(a) Multidiscipline journals such as *Science* and *Nature*, which cover many different disciplines of science, including medicine, physics, and geology. We will refer to them mainly as "general-science journals."

(b) Discipline journals such as *Journal of Geology* and *Geological Society of America Bulletin*, which purport to cover all aspects of the field of geology, including all of its subdisciplines. We will call these "general-geology journals."

(c) Subdiscipline journals such as the *Journal of Geophysical Research* and *Ground Water*, which cover all or part of a particular subdiscipline.

Our goal in this article is to look at how different subdisciplines have changed in influence over the years. We assume that each article in a general-science or general-geology journal is also appropriate for some subdiscipline journal. We use text-classification methodology to classify each general-science and general-geology article into a subdiscipline journal based on similarities of titles and keywords. The strategy is similar to asking the question, "what subdiscipline journal would this article most likely have been published in, if the general journal had not been available?"

2. Related Studies

2.1. Twigging

The growth and branching of a discipline--*twigging*--was first examined in depth by de Solla Price (1961, 1963) in two seminal studies of scientific progress. Specifically, twigging is the tendency of scientific disciplines to divide into smaller subdisciplines, an action usually marked by the spawning of new subdiscipline journals. De Solla Price (1961) found that the number of scientific journals increases exponentially over time, doubling every 15 years. Given an influx of new experimental opportunities, a new paradigm, or new ideas, scientific journals multiply, he says, like rabbits. As the literature grows in volume, scientists tend to divide themselves into increasingly more specialized subdisciplines. Mabe and Amin (2001) suggested that the appearance of new journals

> is the outcome of attractive fusion forces ("going with the crowd" or peer pressure, and the advantages of social interaction) making subject specific social groupings

> grow in number, versus the repulsive, fissile forces (impersonality, clique formation and unwieldy size) tending to split large existing groupings apart. (p. 160)

Mabe and Amin, like many who conduct social studies of science, tend to place emphasis on social forces in science, to the exclusion of such other pressures as theoretical, logistical, and economic forces.

Johnson and Schubert (1989) and Mermin (1988) have a pragmatic explanation for twigging: they point out that as subdisciplines of science get larger, scientists are unable to stay abreast of all the research within their own discipline. Johnson and Schubert use a decrease in comment and reply articles as evidence that the readership is having a more difficult time keeping up with the current literature and notes that this is probably the point at which the discipline is most susceptible to twigging.

In these and other accounts, reactions to the twigging phenomenon are largely negative. Greco, Wharton, Estelami, and Jones (2006), for instance, report that editors of historical journals considered the twigging phenomenon to be a problem, especially in addressing "broad disciplinary issues of scholarship" (p. 180). Comments such as this respond not only to the scientific priority of reading widely, but also to the economic worries of academic libraries forced to subscribe to an ever-increasing number of very expensive journals.

No one has decried the phenomenon of twigging more stridently than one of the giants of geology, M. King Hubbert. He saw the twigging phenomenon as an error in judgment and a direct threat to the quality of geology. After his term as the president of the Geological Society of America (GSA), Hubbert (1963) voiced his fears that the scientific community was falling victim to authoritarianism and sloppy thinking. He asserted that twigging and over-specialization were major causes:

> Another factor involved in our reversion to authoritarianism is a prevailing view of the evolution of science. This is that scientific knowledge has become so vast as compared with the limited capabilities of the individual that one man can only hope to know "authoritatively" a minute fraction of the whole. Hence we are constrained, if we are to avoid being ineffectual scientific dilettantes, to select some limited domain--our "specialty"--of such small size that we are capable of reading all the pertinent literature and hence of mastering all that is known about it. By this premise, all other scientists must do the same with respect to other domains, so that the only way of knowing anything outside of our own specialty is to accept the word of an authority or specialist in that field. Hence, according to this view, we are condemned to accept authoritarianism by the very immensity of human knowledge. (p. 374)

He broadened his criticism of twigging to include its partner phenomenon, cooperative research:

> According to this specialistic view, any scientific enterprise of broader scope than an individual "specialty" can only be carried out by the co-operation of teams representing the various "specialties" involved. Thus one hears repeatedly that the future advancement of science is more likely to be the result of such co-operative teamwork than of work done by individuals; and in current literature papers bearing

> the names of as many as half-a-dozen coauthors are not uncommon.
>
> I do not mean to imply that in many instances such co-operative enterprises, especially on the technician or development level, may not be more effective than the same work done by individuals. There is also no question that the work of any individual must have been based upon what others have done before. It may be well to remind ourselves, however, that thinking is peculiarly an individual enterprise, and that the greatest of scientific achievements--those of the great synthesizers from Galileo to Einstein--have, almost without exception, been the work of individuals. (pp. 376-377)

The concerns of these prominent scientists and editors raise an important issue concerning coherence within a discipline. Incoherence is the trigger that causes a discipline to split into smaller groups, each with a stronger sense of self-identity. This action has real consequences for the progress within a science. Goldman (1979) emphasizes the importance of coherence within a discipline to the quality of science in that discipline. He asserts that one observes several things in a compact, coherent discipline. First, most of the article citations occur within a few core journals, indicating that researchers are building directly upon each other's work. Second, there are few subfields or cliques, indicating that information is flowing freely between researchers in all areas of the field. And finally, publications within the field are easy to locate, ensuring that research is not wasted by replication or lack of citation.

2.2. Little Science, Big Science

De Solla Price's second work in 1963 consisted of an in-depth description of three stages of scientific growth (see also Fernandez-Cano, Torralbo, & Vallejo, 2004; Mabe & Amin, 2001). The first is an initial period of "little science," wherein growth is driven by scientific societies and little funding is available. The second he calls "big science," characterized by widespread government and commercial support and funding. The third phase is marked by a return to lower rates of growth following disappointment, disillusionment, and diminishing government support.

The distinction between little science and big science is, as de Solla Price (1961, 1963) and Weinberg (1961) suggest, a matter of scale. Big science requires many people, lots of equipment, and lots of money. For this large investment, however, big science often produces large numbers of high-impact articles. Ribbe (1988) examined the impact/investment relationship in the field of geology, comparing the impact factor of geology journals and the average amount of funding per paper in those journals. He found a strong positive correlation.

Mabe and Amin (2001) emphasize the importance of a key research event, such as a landmark conference, on the transformation to big science. According to them, such an event engenders a boom in the discipline, an influx of new papers which the editors accommodate by hosting special issues, creating special sections, or founding new journals altogether. They use plate tectonics as one example, citing conferences held in 1964 as key events after which the number of articles on the topic published every year went from 100 to 3,500. The event in question is perhaps the best example of a Kuhnian paradigm shift, and there was a striking difference in geological discourse before and after the event. Geologists scrambled to reinterpret decades of previous research in light of the new theory. Phenomena that could not be explained before were now integrated into more coherent theories.

3. Methods

The data for this study consist of titles and keywords for around 175,000 articles from the GeoRef database. GeoRef is a bibliographic database containing around three million references to geoscience literature, including journal articles, books, maps, conference proceedings, reports, Web sites, and theses. GeoRef was created by the Geological Society of America and is currently maintained by the American Geological Institute. It is the primary bibliographic reference for literature searches in geology and related fields.

We started with GeoRef's list of priority journals, excluding articles published in special issues or monographs, as well as abstract-only documents and conference proceedings. Some journals were excluded because their earlier volumes have not been entered into the database or were published in languages other than English. Other excluded journals began publication late enough in the time period of interest to have only a few years of record.

The rest of the journals fell easily into three groups: general-science journals (*Nature*, *Science*), general-geology journals (*GSA Bulletin*, *Geology*, *Journal of Geology*, *Geological Magazine*, *Canadian Journal of Earth Sciences*, *Journal of the Geological Society of London*, *Precambrian Research*, and *Quaternary Research*), and 60 subdiscipline journals. The only articles from the general-science journals included in the GeoRef database are those directly pertaining to the geological sciences.

We used only articles published between 1945 and 2000, because bibliographic data prior to 1945 are incomplete for many important journals, and because proliferation of geologic journals did not begin in earnest until the 1960s. Prior to 1945, the periodical geology literature consisted of about a dozen journals publishing at a relatively constant rate.

We let each subdiscipline journal define a class representing an area of study. By letting the boundaries of the subdiscipline journals stand in for the boundaries of geologic subdisciplines, we eliminated any subjectivity in creating our list of subdisciplines.

The boundaries of a particular journal's topical focus are set by eminent practitioners in the field (serving as editors and/or reviewers) to delineate the domain of that particular area of research. Their intent is to isolate papers of a particular kind and focus research activity in order to produce more papers of that kind. This process is reminiscent of biological speciation and, we think, supports our treating of these journals as natural classes. Research in information science supports this treatment: although there is often overlap between journals in the same field of study, the titles and keywords of articles within a journal are much more similar to each other than they are to those of articles from other journals (White & McCain, 1989).

General-geology journals and general-science journals report on several subdisciplines at once and should therefore have articles that are, in our topic space, scattered among the clusters of subdiscipline-journal articles. In this study, we want to find out how many of the general-geology articles fall within each subdiscipline-journal cluster, and how this changes over time. This is a classification problem.

We created a nearest-neighbor classification model using *WordStat 5.1*, a text-analysis module for the Provalis *Simstat* software. During the learning phase of classification, we simply represent each article in the learning set (the subdiscipline journals) by a point in a multi-dimensional space. Each dimension in this multi-dimensional space refers to the presence or absence of a particular word--*earthquake*, *mineral*, *basalt*, and *foraminifera*, to name a few. Articles whose title and keywords contain similar sets of words will be positioned close to each other in this space, whereas dissimilar articles will be positioned further apart. The distance was calculated as a simple Euclidian distance between the two points.

The class corresponding to a specific subdiscipline journal consists of a list of point locations--one point for each article in that particular journal. During the classification phase, we assigned each "unknown" article from a general-science or general-geology journal to the class that contains the point nearest to it.

Although we started with a word list containing tens of thousands of unique words (and an equal number of dimensions), we were able to reduce the number of dimensions in our classification vector space by eliminating all words that occurred in more than 60 percent of the records or in fewer than 10 records. Any word lemmatization or dictionary classification was moot, as the vocabulary of geology is so specialized as to render English-language dictionaries unusable. Capitalized words were overwhelmingly place names or the names of geologic formations and were therefore ignored. We compiled the final model using a vector space of 1,000 dimensions corresponding to the 1,000 words with the highest global chi values--that is, the words that best distinguished one journal from the rest. For example, the word "earthquake" has a very high chi value because the presence of this word correlates well with membership in a particular class--the class corresponding to *Bulletin of the Seismological Society of America*.

To test the effectiveness of these classification methods, we ran the learning phase thousands of times, leaving a different subdiscipline-journal article out of the classification each time. We then classified the article to see if it ends up in the subdiscipline-journal class that it actually belongs to. The model was about 98 percent accurate; during cross-validation, the classifier misclassified only 623 out of 30,837 articles. A review of the misclassified articles revealed that the articles were in fact appropriate for the journals that they were sorted into. Misclassification in this case is not considered a measure of error within the model, but rather an indicator of similarity between journals.

Table 1. *Geoscience Journals Included in the Study* (The journals are in the same order as they appear in Figure 1, from left to right, and are color-coded similarly.)

	Computational Geology		*Journal of Geophysical Research*
	Mathematical Geology		*Bulletin of the Seismological Society of America*
	Paleoceanography		*Geophysics*
	Marine Geology		*Precambrian Research*
	Palaeogeography, Palaeoclimatology, Palaeoecology		*Quaternary Research*
	Earth Surface Processes and Landforms		*Geology*
	Geoderma		*Canadian Journal of Earth Sciences*
	Environmental and Engineering Geoscience		*Geological Magazine*
	Hydrological Processes		*Journal of the Geological Society of London*
	Quarterly Journal of Engineering Geology		*Journal of Geology*
	Engineering Geology		*Geological Society of America Bulletin*
	Soil Science Society of America Journal		*European Journal of Mineralogy*
	Water Resources Research		*Physics and Chemistry of Minerals*
	Ground Water		*Lithos*
	Journal of Hydrology		*Clays and Clay Minerals*
	Journal of Metamorphic Geology		*Contributions to Mineralogy and Petrology*
	Journal of Structural Geology		*Journal of Petrology*
	Sedimentary Geology		*The Canadian Mineralogist*
	Sedimentology		*American Mineralogist*
	Journal of Sedimentary Research		*Mineralogical Magazine*
	Global Biogeochemical Cycles		*Palaios*
	Applied Geochemistry		*Journal of Vertebrate Paleontology*
	Organic Geochemistry		*Journal of Foraminiferal Research*
	Chemical Geology		*Palaeontology*
	Geochimica et Cosmochimica Acta		*Micropaleontology*
	Meteoritics and Planetary Science		*Journal of Paleontology*
	Geophysical Journal International		*Journal of Geochemical Exploration*
	Tectonics		*International Journal of Coal Geology*
	Bulletin of Volcanology		*Journal of Petroleum Geology*
	Journal of Volcanology and Geothermal Research		*Mineralium Deposita*
	Physics of the Earth and Planetary Interiors		*American Association of Petroleum Geologists Bulletin*
	Tectonophysics		*Economic Geology*

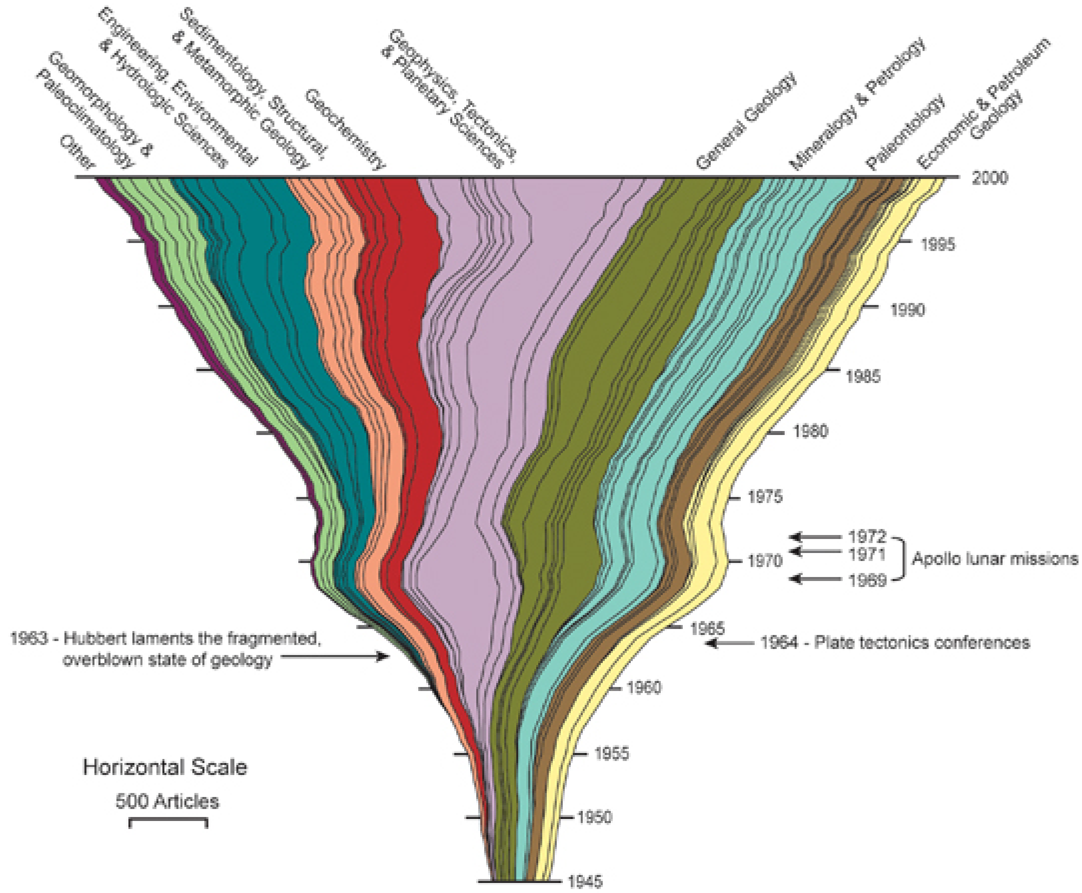

Figure 1. Number of articles published each year in the 68 geology journals in this study. Individual journals are grouped into broad topical areas, indicated by color. The individual journal titles in each topical area are given in Table 1.

4. Results

4.1. Volume of Geology Literature

For the geology journals included in this study, annual publication rate rose from fewer than 500 articles per year in 11 journals in 1945 to a total of around 6,500 articles per year in 68 journals in 2000. Figure 1 shows the actual number of articles in 68 journals over 55 years. (These are not the results of the classification exercise--these are the actual number of articles published in each of the 68 geology journals over this time frame.) The figure indicates that four major areas of study within geology have been a large part of the geological literature since the early part of the twentieth century: (a) economic and petroleum geology, (b) general geology, (c) mineralogy and petrology, and (d) paleontology. Sedimentology, geochemistry, and the geophysical subdisciplines developed soon after World War II. Engineering geology, environmental and hydrological science, and the geomorphology-paleoclimatology group are more recent additions to the constellation of geology subdisciplines. General-geology journals are included in Figure 1, grouped under their own heading, to illustrate their contribution to the volume of geologic literature.

Comparing the early years at the bottom of the figure to recent years at the top shows that the group of journals representing geophysics, tectonics, and planetary science has expanded proportionately more than any other group. This growth is due in large part to the *Journal of Geophysical Research*, which split into seven subjournals. Only parts A (*Space Physics*), B (*Solid Earth*), and E (*Planets*) met our qualifications to be included in this study. On the other hand, economic and petroleum geology, sedimentology, and paleontology groups have stagnated when compared to the rest of the geologic literature.

Marring the monotonic expansion of geologic literature is the transient glut of articles published in response to the Apollo lunar landings in 1969, 1971, and 1972. The journal that absorbed most of the lunar-landing-related output is the *Journal of Geophysical Research*, which, in Figure 1, has a pronounced bulge centered on the early 1970s.

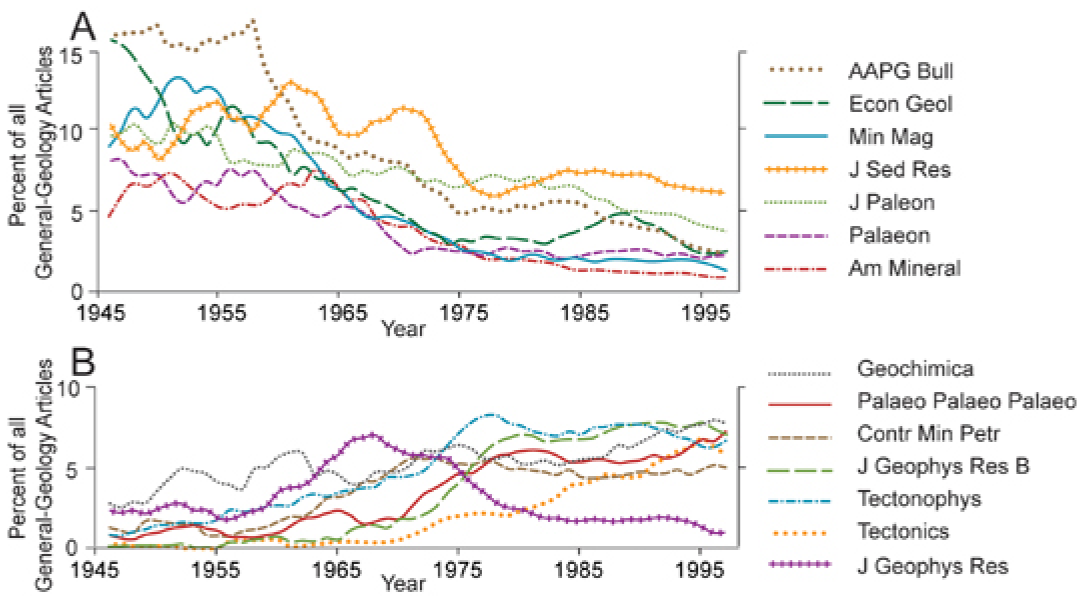

Figure 2. Percentage of all general-geology articles by subdiscipline-journal classification. Lines represent 5-year running average. Panel A: Classes whose relative influence decreased over the study period. Panel B: Classes whose relative influence increased over the study period. Subdiscipline-journal classes that never constitute more than 5 percent of the classified articles are not included in this graph.

4.2. Trends in General Geology

Each general-geology article was assigned to a *subdiscipline-journal class*. For the entire body of general-geology articles, 14 major classes captured most of the articles. It appears that the areas of study represented by each of these subdiscipline journal classes either gained or lost influence over the study period, as evidenced by changes in the percentage of general-geology articles assigned to that particular class over the 55-year span (Figure 2). For instance, the *Bulletin of the American Association for Petroleum Geologists*-class (*AAPG Bulletin*) shows considerable influence in the 1940s and 1950s: around 16 percent of the articles published in general-geology journals during those years were classified as *AAPG-Bulletin*-type articles

(Figure 2). The relative importance of the journal falls off over the next several decades, however, and only about 3 percent of articles published around the year 1995 were in the *AAPG-Bulletin*-class. The *Economic Geology*-class exhibits similar behavior. The percentages of articles matching those in the sedimentology-class, mineralogy-class, and paleontology-class journals (all the other journals in Figure 2A) underwent less precipitous declines over the entire study period.

The journal classes depicted in Figure 2B, on the other hand, all increased slightly in importance over the study period, except for the *Journal of Geophysical Research*-class, which peaked in the late 1960s and declined again near the end of that decade to give way to articles that fit more appropriately into one of its subjournals, the *Journal of Geophysical Research B (Solid Earth)*-class. However, none of the journals achieves the same level of importance that *AAPG Bulletin*-class and *Economic Geology*-class had in the 1940s. In fact, the topics specific to those two journals alone account for about one-third to a quarter of the general-geology articles prior to 1960.

Subdiscipline-journal classes that increased in influence over the study period also included those corresponding to two tectonics journals (*Tectonics* and *Tectonophysics*), two geochemistry-related journals (*Geochimica et Cosmochimica Acta* and *Contributions to Mineralogy and Petrology*), and *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, a journal dominating the field of palaeo-environmental geology.

Neither graph includes any classes corresponding to hydrogeology journals or environmental science journals. These classes never captured more than 5 percent of the general-geology articles.

Figure 3. Classification of articles from individual general-geology journals. Each pair of bars represents the percentage of articles sorted into a particular subdiscipline-journal class, one bar for the year 1945 and one bar for the year 2000. Three journals started publication after 1945, so the first bar represents the journal's starting year: they are *Geology* (started in 1973), *Precambrian Research* (started in 1974), and *Quaternary Research* (started in 1970). The bar pairs are sorted according to their ranks in 2000. The subdiscipline journals constituting the largest percentages of articles for 1945 and 2000 are labeled on the diagram.

When we look at each individual general-geology journal and how its articles were classified in 1945 and 2000, we see that each journal-class has undergone an overall shift in emphasis (Figure 3). The labeled classes near the bottoms of the bar graphs have suffered a sharp decline in prominence, as shown by the difference between their 1945 and 2000 percentages: the classes corresponding to the *AAPG Bulletin*, *Economic Geology*, *American Mineralogist*, *Journal of Palaeontology*, and *Journal of Geophysical Research* are examples that lose influence (move downward) in several of the general-geology journals. In contrast, many of the journals near the top of the bar graphs have shown an increase in prominence (moved upward), such as the classes corresponding to the *Journal of Geophysical Research B*, *Tectonics*, and *Tectonophysics*. However, some near the top of the graphs have actually decreased in the percentage of articles since 1945; for example, the *Journal of Sedimentary Research*-class within the *Journal of the Geological Society of London*, or the *Palaeontology*-class within the *Geological Magazine*. This reflects an increase in diversity among those two general-geology journals. Instead of publishing articles that fall into two or three classes, these journals are publishing articles that are spread among many different subdiscipline classes. Here, as in Figure 2, we see a general shift from economic geology, mineralogy, and paleontology to tectonics, geophysics, and geochemistry. Also as in Figure 2, hydrogeology, engineering geology, and environmental geology subdiscipline classes are poorly represented within the journals in Figure 3.

Each general-geology journal has its own recipe for content. The *Geological Magazine* alone continues to focus on paleontology and sedimentary research, with a sharp drop in mineralogy content. The *GSA Bulletin* has undergone a dramatic shift in focus from *AAPG Bulletin* and *Economic Geology* content to that of geophysics and tectonics journals. The *Journal of Geology* has a similar history to the *GSA Bulletin*, except that it has more of a focus on articles appropriate to *Contributions in Mineralogy and Petrology*. The *Journal of the Geological Society of London* had many articles similar to those found in the *Journal of Sedimentary Research*. This sedimentary-research subdiscipline has been edged out by the *Tectonophysics*-class, but still remains a dominant subdiscipline class. Articles from the *Canadian Journal of Earth Sciences* have always been spread out over many different subdisciplines--this journal began in 1963, so there has not been as much opportunity for change. *Geology's* footprint is not drastically different from its mother journal *GSA Bulletin*. The only major development in *Geology* is that the *Journal of Geophysical Research*-class was supplanted by the *Journal of Geophysical Research B*-class in its prominent position.

Precambrian Research has a profile not unlike those of the other general- geology journals, except steeper and less distributed among the subdiscipline journals. However, *Quaternary Research* is dominated by articles that would fit the subdiscipline journal *Palaeogeography, Palaeoclimatology, Palaeoecology*, and has been since its inception in 1970.

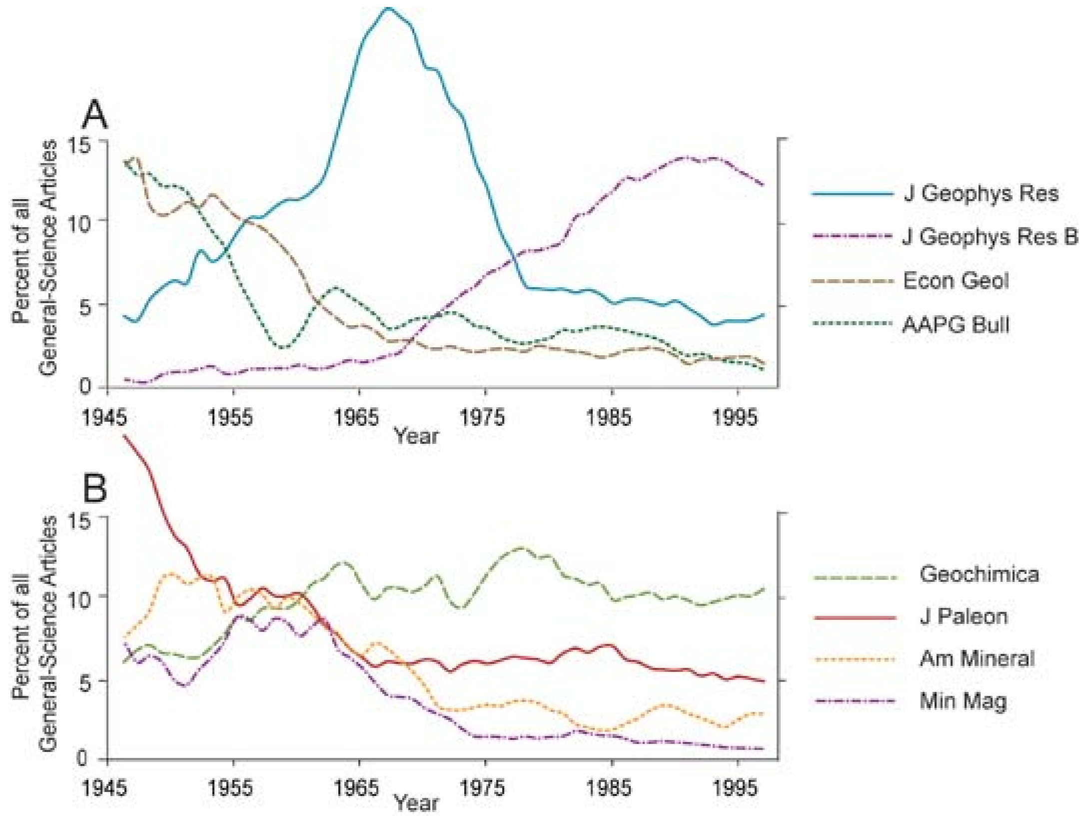

Figure 4. Percentage of all geology articles from general-science journals by subdiscipline-journal classification. The eight classes shown are divided among panels A and B for better visibility. Journals that never constitute more than 5 percent of the classified articles are not included in this graph. Lines represent 5-year running average.

4.3. Trends in General Science

From 1945 to 2000, there were 23,000 geology articles published in the general-science journals. In the early 1970s, fully 20 percent of these fit the profile of articles published in *Journal of Geophysical Research* (Figure 4). As in the general-geology articles, the influence of this journal gives way to a rise in articles that fit into its *Solid Earth* offspring. The *Journal of Paleontology*-class decreases from 20 percent of articles around 1945 to 5 percent of articles from 1965 on. The *Geochimica et Cosmochimica Acta*-class retains around 10 percent of the general-science articles from 1965 on. The other journals decrease drastically in the 1950s and 1960s. Notably absent from these graphs are not only the classes corresponding to hydrogeology, engineering geology, and environmental science journals, but also those corresponding to the two tectonics journals.

5. Discussion

5.1. Trunk and Twig

Clearly, geology has followed the trend outlined by de Solla Price (1961, 1963), growing and twigging over the past 60 years or so. Within the scope and limitations of our body of journals, de Solla Price's rule of approximately 15-year doubling rate of journals in a field appears to be more or less true for geology (Figure 1). Eleven of the journals in this study were extant by 1945; in 1960, the number had grown to 19, and in 1975, 43 of the priority journals included in our study were in existence.

A possible reason for twigging is made clear in Figure 1: the specialized subdiscipline geologist has more reading to do to keep up with a subdiscipline today than the geologist in 1945 had to do to keep up with the entire discipline of geology in 1945. This is both cause and result in a feedback loop that ever increases the number of geologic specialties. It appears that Hubbert's vision for the future was correct, in a way. He lamented that geologists, who consider themselves students of the earth,

> have tended to become students of minerals, of rocks, of ore deposits, of coal, of petroleum, of strata, of fossils, of deformational structures, of volcanoes, of erosion and landforms, and of the physics and the chemistry of the earth. (1963, p. 377)

Indeed, the small cluster of geology journals has blossomed into an array of journals focused on different subdisciplines, specialties, and subspecialties. Ironically, Hubbert made his comments over 40 years ago, before most of these journals came into being (Figure 1)! The problem is clearly more advanced than even he anticipated. But, contrary to his expectations--and contrary to the worries of geologists decades later--the latter half of the twentieth century has been perhaps the most productive in the history of geology.

Perhaps twigging, instead of inhibiting scientific growth, acts as a self-preservation mechanism for a particular discipline. Surely the splitting of an overlarge, unconsolidated discipline would result in smaller but more cohesive units. Might not work within these specialties then proceed more efficiently than before? That geology has expanded without serious interruption for half a century into an increasingly multifaceted state would certainly support this notion.

Regardless of whether twigging is a liability or an asset, there are striking differences between the science of geology at the trunk stage and at the twig stage. Research geologists now seem to have little resemblance to the iconic adventurers and explorers of the early 1900s, whose life works were usually contained within a handful of enormous, place-related monographs. Hubbert's complaint might easily be read as a lament of the passing of a particular, geologic way of life. Other geologists have also been cautious at the replacement of basic, field-based geology with over-technical, over-specialized fields of study. Those drawn to geology during the times of the lone researcher in the field with a pack mule and rock hammer would indeed have a difficult time adjusting to the large-scale, collaborative research projects in which each person plays only a small part. In short, during the last half-century, geology shifted from little science to big science.

5.2. Little Geology, Big Geology

Plate tectonics is cited by many to have provided the fuel for geology's rapid expansion in the latter half of the twentieth century (for example, Oldroyd, 2002). However, there is another important element to the shift in geologic consciousness, one which has a very specific onset: July 20, 1969. GSA President Morgan J. Davis commemorated the event as it passed:

> It has been my good fortune to have served as President of GSA during probably the most momentous year the geological profession has ever known. I refer, of course, to the lunar landing and the subsequent opportunities afforded to some of our colleagues to examine the first rocks ever brought, by man, back to Earth from another member of our solar system. (Davis, 1970, p. 331)

The lunar landings were part of, as another GSA president put it, a "double-barreled revolution of plate tectonics and planetary exploration" (Ernst, 1987, p. 2). The lunar samples and the intellectual fervor that they created were nowhere more profound than in the field of geology. More than an interesting but unrelated side note to the history of modern geology, the event produced a shift in scientific consciousness as fundamental as that resulting from the plate tectonics revolution (Oldroyd, 2002).

> While important parts of geology became inextricably linked with physics, partly as a result of the plate tectonics revolution, it also became entwined in the latter part of the twentieth century with space science and aeronomy, so that we now find congresses in which the participants are partly earth scientists (seismologists, geomagneticians, tectonics specialists, etc.) and partly space scientists and space engineers . . . or even astronomers.
>
> The study of the Earth is now enriched by investigations of the Moon and planets. Geomagnetic studies (so important in the plate tectonics revolution) are linked to investigations of the Sun, the ionosphere, etc. Studies of movements of faults and plates are facilitated by the use of new techniques such as GPS, themselves made possible only by the work of artificial satellite engineers. Well before the end of the twentieth century, one of the leading journals for geologists was Earth and Planetary Science Letters. On the other hand, it should be emphasized that the effect of plate tectonic theory on the day-to-day activities of many geologists, particularly applied geologists, was often quite small. (p. 4)

The lunar missions and subsequent study of the lunar samples constitute one of the best examples of a big science event throughout geology. Millions of dollars, thousands of people, and dozens of research institutions were involved in the undertaking. Mabe and Amin (2001) mention it as an example of big science (though they made no mention of its effects on geology). The deluge of scholarly articles directly concerning the lunar samples is transient (Figure 1); however, several years later the *Journal of Geophysical Research* spun off the subjournals *Planets* and *Space Physics*. Countless other geology-and-space journals now support the new subdisciplines spawned as a result of this event. Note that we structured this study to eliminate transient events such as this by excluding monographs and special issues from our data set. Its prominence in our results only emphasizes its impact on geology.

Implied, but not directly stated, in accounts of big science is the presence of the specialist. Big science uses expensive equipment and teams of scientists. We may infer that each person on the team has more or less a singular role in the team. It is as Hubbert feared: each scientist, being a specialist in a particular discipline, will probably never comprehend the totality of the group's research. However, the fact remains that big science cannot be undertaken by a single person. Neither Galileo nor Einstein, with his staggering genius, could bring rocks back from the moon.

5.3. Discipline Drift

In his description of the impact of the lunar landings on geology, Oldroyd (2002) speaks in terms of tangible changes in the structure of the science. However, both that event and the plate tectonic revolution also instigated small but pervasive changes in the discourse of geology. By characterizing the journal classes in terms of keyword and title vocabulary, we have begun to quantify the change in the structure of the field of geology by measuring these subtle shifts in language. In doing this, we have traced the rise and fall of several major geologic specialties.

Four major groups of journals can be traced back to World War II: (a) general geology, (b) mineralogy and petrology, (c) paleontology, and (d) economic/petroleum geology (Figure 1). These long-lived journals reflect the early development of geology as a field, which evolved along two major lines: the investigation of earth materials (mineralogy and petrology) and the support of mining and engineering (Laudan, 1987). Paleontology evolved along with biology and the investigation of Earth's history, and the practice of science within early scientific societies gave rise to the general geology journals (Porter, 1978).

Despite their importance in the early history of geology, the three oldest subdisciplines have fared badly in keeping up with the expansion of the field. For instance, the absolute number of general-geology articles having to do with economic and petroleum geology has not changed substantially over the 55-year study period. As the other subdisciplines expand rapidly, the relative importance of economic and petroleum geology articles drops. Other areas of study have gained some of the ground that these subdisciplines have lost:

(a) Articles incorporating plate tectonics terminology are a substantial part of the general geology literature now. Although the plate tectonics revolution itself has been studied from many different angles, this study shows the most material change that it made in the science of geology. As Oldroyd pointed out, plate tectonics may not have drastically affected the daily operations of the average geologist. It has, however, substantially revised the geologist's vocabulary. Over the time span covered in this study, the advent of plate tectonics brought into the geologic literature an array of terminology that has embedded itself permanently in our geologic lexicons. As a unifying theory for geology, plate tectonics pervades geologic thought and vocabulary at almost all levels. Thus, even articles that are not substantively about plate tectonics show the influence of terms associated with the theory. It is these terms that our classification model picked up on when sorting articles into the *Tectonics*- and *Tectonophysics*-classes. Perhaps it is this pervasiveness of thought and word that philosophers acknowledge when they cite plate tectonics as the quintessential paradigm shift, even though they seldom agree on the degree and impact of the actual changes that took place (for instance Frankel, 1978; Kuhn, 1962; Laudan, 1978; Le Grand, 1988; Ruse, 1978; Solomon, 1992).

(b) The impact of the lunar landings on the *Journal of Geophysical Research*, the general-science journals, and the general-geology journals shows that the bulk of the literature explicitly treating the moon rocks came and went in the early 1970s. As with plate tectonics, however, planetary exploration has effected permanent change in the science of geology. From 1969 on, the Earth has been seen primarily as a part of an evolving solar system. Increasingly, man-made satellites are used to gain an extra-terrestrial view of various earth features. Evidence of this event's lasting impact is visible in the continued existence of related journals, and in the influence of topics in articles in general-science and general-geology journals.

(c) Before the 1950s, paleontology was more than simply a subdiscipline of geology. It was the major tool used by geologists to determine the relative ages of rock formations. This particular use of paleontology was once an integral part of any geologic study and a vital tool in petroleum exploration (Weller, 1947). However, the development and popularization of mass spectrometry and related techniques allowed isotopic dating procedures to supplant biostratigraphy as the main method for constraining rock ages. Paleontology has since suffered a decline in status as a geologic subdiscipine, with material decreases in the number of practitioners, course offerings, students, and job opportunities (Cooper, 1958; Lane, 1989; Radenbaugh, 2005).

5.4. Pure Geology, Applied Geology

It would be tempting to say that the apparent decline in importance of petroleum and economic geology articles simply parallels an actual decline in production of economic minerals, punctuated by the closing of the US Bureau of Mines in 1996. To a certain extent this is true (Ernst, 1987). Although the production of minerals in the United States has since recovered from the recessions in the 1970s and 1980s, the onset of environmentalism prevented a return to the status quo (Tilton & Landsberg, 1997). Mining companies and petroleum companies are now under strict obligations towards the environmental status of the areas that they exploit. The financial burdens of environmental regulations drove many smaller mining firms out of business, and changed the net value of mineral deposits by making them much more expensive to extract. At the same time, progress in mining technology and a strict eye on the bottom line increased the efficiency of mining operations (Energy Information Administration, 2007), causing a relative decrease in the personnel needed per ton of mineral extracted, and causing the role of the geologist in mining to change altogether (Chase, Newman, & Rusnak, 2006).

However, there is more going on than economic factors can account for. Taken together, petroleum and mining industries have not become less important or influential to geology or society as a whole. They seem to have all but disappeared from the general geology journals, however. Similarly, environmental geology is not represented at all on the charts in this article, even though it is considered by many to be the major focus of geology in the current decades (for example, Ernst, 1987; Zoback, 2001) and is a major employer of geoscientists. In fact, it is interesting to compare Figure 1 with what we know about geologic employment. According to the National Survey of College Graduates (conducted by the National Science Foundation, USA), in 1993, 95 percent of the working geologists surveyed were in industry, consulting, and federal government in the areas of petroleum, mining, and environmental geology. None of the major journals in each of these fields constitutes more than 5 percent of articles in the general-geology (Figure 2) or general-science journals (Figure 3). There is still a respectable rate of publication *within* subdiscipline journals for each of these fields. That they are grossly under-represented in the general-science and general-geology journals indicates that the separation between pure and applied geology is all but complete.

The dichotomy between pure and applied geology is only one of several pairs of bipolar descriptors that apply to the general trends of geology in the past half-century. Many scientists have noted a trend away from more observational methods of working towards theoretical concerns:

> I believe examination of the pages of the Society's Bulletin will show a progressive increase in emphasis on principles, rather than observations, and should be regarded as characteristic of the intermediate stage in the development of the science. (Nolan, 1962, p. 274)

These are generally assumed to be a sign of maturation in a science. During the maturation process, a science is also assumed to move from the field to the laboratory, becoming more experimentally driven as time goes on (Battalio, 1998; Bazerman, 1984). These trends show up in the results of our classification exercise. Movement away from descriptive subdisciplines like paleontology and sedimentology, and towards subdisciplines like geophysics and geochemistry, indicates that geology as an area of research is becoming an increasingly pure, physics-based science. The shift towards a "purer," more laboratory-based version of geology is consistent with reported pressures on the science from years past, and it accords with expectations of geologists in the big science era.

6. Conclusions

In the last half of the twentieth century, geology changed. This much is obvious to geologists and observers alike. Our study of the connections between multi-discipline, discipline, and subdiscipline journals shows that geology has expanded and fragmented into ever-smaller subdisciplines according to the expectations of de Solla Price and the fears of Hubbert. It has been boosted into the realm of big science with help from two powerful events: the unifying theory of plate tectonics and the intense burst of interest inspired by the lunar landings. These two events have also left lasting marks on the language and literature of geology, evidenced in the influence of tectonics journals and planetary-science journals on general geology.

Over the same timeframe, applied and pure geology have fully separated. In the general-geology and general-science journals, there has been a large drop in emphasis on applied geology. This move reflects not only the difficulties experienced in the fields of petroleum and economic geology, but also the movement of geological research towards purer, more quantitative physics- and chemistry-based methods and theories.

Geologists, in studying the past, learn about the present. Our information-science-based investigation of 55 years of articles in the GeoRef database puts the current state of geology and geoscience education into perspective. An increasing number of geoscience teachers are concerned that geoscience education lags behind in providing our students the quantitative skills they will need to prepare for geological research or to practice geology (for example Macdonald, Srogi, & Stracher, 2000). From a historical base in which undergraduate geoscience has been dominated by the rock-hammer paradigm, and a curriculum of sample identification and descriptive field mapping, the new world of geoscience is one in which physics, chemistry, and numerical methods are pervasive core concerns; they are no longer peripheral issues that would come into play in one or two courses. Our study suggests that, until geoscience education catches up with the quantitative-skills needs required for modern geoscience, this is an unstable situation. Education, after all, must anticipate the prerequisites of future research practice in order for the science to advance.

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