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Article abstract

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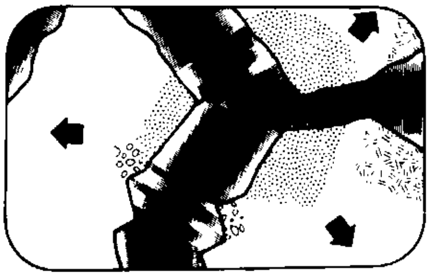

The Breakup and Dispersion of a New Conceptual "Continent"

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Abstract
The recently developed technique of 'co-citation analysis' is used to examine intellectual developments in the geosciences from 1970 to 1975. The results for 1970 show a cluster of plate tectonics articles that are often cited together, and a 'picture' of these articles and their interrelationships is presented as a series of interconnected hills - one hill for each article. Results for 1973 and 1975 indicate the rise of new clusters of articles associated with new research interests, e.g., 'hot spots', and the dispersion of the original cluster of plate tectonics as this theory was applied to other areas, e.g., continental geology. These results are presented so that geoscientists can assess the ability of this new technique to identify changing theoretical interests in science.

Introduction
Contributions to geological knowledge may arise from the development of new instruments or new models. For example, the development of the sea-going magnetometer and the interpretation of its output in terms of the sea-floor spreading model were important elements in the rise of plate tectonics theory. Similarly, contributions to the history and sociology of science may arise from new measurement procedures or new models. For example, new techniques for examining citation patterns in the scientific literature may be related to models of scientific development. Like a rock's natural remanent magnetism, some charactertistics of scientific articles provide information about the conditions in the surrounding intellectual environment. This article reports results from the examination of the citations in over two million scientific articles that were dated as forming between eleven and six citing years (cy) ago, i.e., published from 1970 to 1975. These results indicate that eleven cy ago there existed a conceptual "continent" composed of plate tectonics articles. During the next five citing years, this "continent" fragmented, new "continents" formed over "hot spots", and various fragments drifted together again. The motive force behind this "continental drift" appears to be a combination of "hot spots" and convection currents in the mantle of consciousness.

The purpose of this article is to describe the inferred pattern of drift so that geoscientists, whose citation patterns created these continents, can assess the validity of the results. The first section briefly describes the "co-citation analysis" procedures used to identify and portray the conceptual continents. The second section provides topographic pictures of selected continents, their relative locations in a two-dimensional "conceptual space", and suggests how these results may reflect changing cognitive interests in the geosciences.

Co-citation Analysis
The basic assumption in co-citation analysis is that two references are considered more closely related the more they are cited together - co-cited - by later articles (Small and Griffith, 1974; Griffith *et al.*, 1974). Although there are several possible methods of examining co-citation information, the following steps were used to generate the figures in the next section.

Isolating major groups of references. The first step isolated major groups of references that were more highly co-cited to other references within the same group than in other groups. Each group is assumed to represent the major references within a fairly specific area of research. These groups were isolated by the following procedures. First, all the references cited 15 or more times in an annual issue of the *Science Citation Index* - for each year from 1970 to 1975 - were separated from the other publications. Second, all possible pairs of these highly cited references were formed and counts were made of those articles that cited both references in each pair. This gave the number of co-citations per pair of references. Third, these co-citation counts were "normalized" to give the proportion of citations to the two references that were co-citations; if c_1, c_2, and c_{12} are the number of citations to the two references and their co-citations, then the normalized score is $c_{12}/(c_1 + c_2 - c_{12})$. This corrects for the fact that some pairs may be more highly co-cited because each member of the pair is highly cited. Finally, the matrix of normalized scores between the pairs of references was put into a single-link clustering program that isolated groups of references whose members were linked directly or indirectly with a normalized score of .16 or higher. For the years from 1970 to 1975 these co-citation procedures isolated one or more clusters of references associated with plate tectonics research.

Representing the relationships among references in a group. The results of the first step could be presented by a simple listing of each group's references, which presumably consist of the major references in a specific research area. However, these references may vary in their centrality and importance to the research area and the second step of analysis was concerned with representing the relative "importance" of the individual references within a group and their relative "position" with respect to each other. The total number of citations to each individual reference was assumed to reflect its "importance", while the number of co-citations between a pair of references was used to indicate the "distance" between the two references, e.g., references that are highly co-cited are assumed to be "close together" in some dimensional space. Given a quantitive measure of the "distance" between each possible pair in a group of N references, it is possible to "map" their relative locations in N-1 dimensions. For ease of visualization, however, the relative locations of the references in each group were constrained to two dimensions, with the third (vertical) dimension reflecting the importance of the reference. This was accomplished by using Small's (1974) "hill" model to represent each reference and to calculate the distance between any pair of references.

Small suggested that we imagine each reference as centered at a specific location within a two dimensional "subject space". However, a reference was not represented as a point in this space, but rather as a smooth "hill" - specifically, a

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bivariate normal density surface - whose volume was equal to the number of citations to the reference. The distance between any pair of hills or references in this subject space was found by overlapping their respective hills until the volume of overlap equaled the number of co-citations between them. Figure 1 is a schematic for the importance of and distance between two references, A and B: the volume of each hill equals the number of citations to the reference and the volume of overlap, AB, equals the number of co-citations to the reference pair. Small (1974) shows how the distance, D, between two references may be calculated from the formula for a bivariate normal density surface, the counts for citations and co-citations, and a standard deviation assigned to each hill's density surface. On the assumption that references with many high normalized scores covered a broader "area" in the conceptual space, each hill's standard deviation was set to the sum of all .10 or above normalized scores between the reference and any other reference in the cluster.

A Smallest Space Analysis (SSA) program (Guttman, 1968; Lingoes, 1965) was used to locate the relative position of each hill in a two dimensional space, i.e., SSA takes the matrix of *one*-dimensional, paired distances among the N references in a cluster and calculates a set of two-dimensional coordinates that minimizes the differences between the one-dimensional and the two-dimensional distances. The final procedures consisted of taking each reference's hill, placing its peak over its location in the two-dimensional space, and using a computer graphics program to portray the upper surfaces of the overlapping hills. Before this final plotting, however, all the hills' variances were divided by two or four to produce steeper and more distinctive hills. This latter procedure was necessary because some of the SSA distances were so much shorter than the initial one-dimensional distances that some hills were concealed by larger, adjacent hills. Thus, in the figures representing the references in each cluster the volume of each hill is proportional to the number of citations to each reference. The distance between the hills indicates how much they were co-cited, but only approximately because the initial distances among the references were distorted by being forced into only two dimensions. More details about the construction of the hill figures may be found in Stewart (1979).

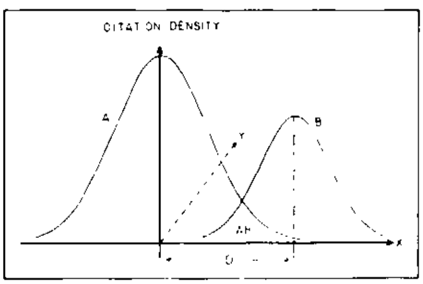

Figure 1 *Density curves above the x-axis for two bivariate normal density surfaces separated by a distance, D. Each "hill" represents one scientific article, the volume under the hill equals the number of citations to the article, and the volume of overlap equals the number of co-citations to the pair of articles. The distance, D, between a pair of articles is uniquely determined given the above information and a value for the standard deviation of each hill.*

Representing the relationships between clusters. A simpler procedure was used for the figures illustrating the relationships *between clusters*. The only available information for this analysis was the number of *intercluster* co-citation counts greater than zero, i.e., where each reference in the pair was from a different cluster. These counts were divided by the number of possible, intercluster pairs and Smallest Space Analysis was used to map the cluster locations in two dimensions. Each cluster will be represented by a circle with an area proportional to the number of articles in the cluster and centered at the cluster's location in the two dimensional space.

Results

One of the major clusters that appeared in every year from 1970 through 1975 included major plate tectonics articles. Figure 2 is the hill model for this cluster of articles in 1970 and it shows the progressive development of a sea-floor spreading "ridge" starting with Hess's (1962) and Dietz's (1961) initial proposal of the sea-floor spreading hypothesis, followed by Vine and Matthews' (1963) hypothesis connecting the linear magnetic anomalies to the sea-floor spreading model, Vine's (1966) verification of this connection, and culminating in the Heirtzler *et al.* (1968) application of the model to the major oceans of the world. The major peaks are, of course, the three plate tectonics articles by LePichon (1968), Morgan (1968), which is concealed by the LePichon hill, and Isacks, *et al.*, (1968). (To get a rough idea of the results of the procedures used to generate this figure, note that in 1970 LePichon (1968) was cited 105 times, Vine (1966) 67 times, and Hess (1962) 37 times. There were 31 co-citations between Vine (1966) and LePichon (1968) and 16 between Vine (1966) and Hess (1962).) McKenzie and Parker's (1967) article is also associated with this group of major peaks. All of these articles are the major publications that first applied the general plate tectonics model to the oceans and illustrated the implications of it for oceanography and seismology. Wilson's (1965a) article proposed the plate concept as an implication of the transform fault concept, which was supported by the Sykes (1967) study. These two articles provide another ridge connecting the Hess hill with the plate tectonics peaks. The Sykes (1966) article, which deals with Benioff zones, is the only one of several other articles with sufficiently strong co-citations to these major articles to allow

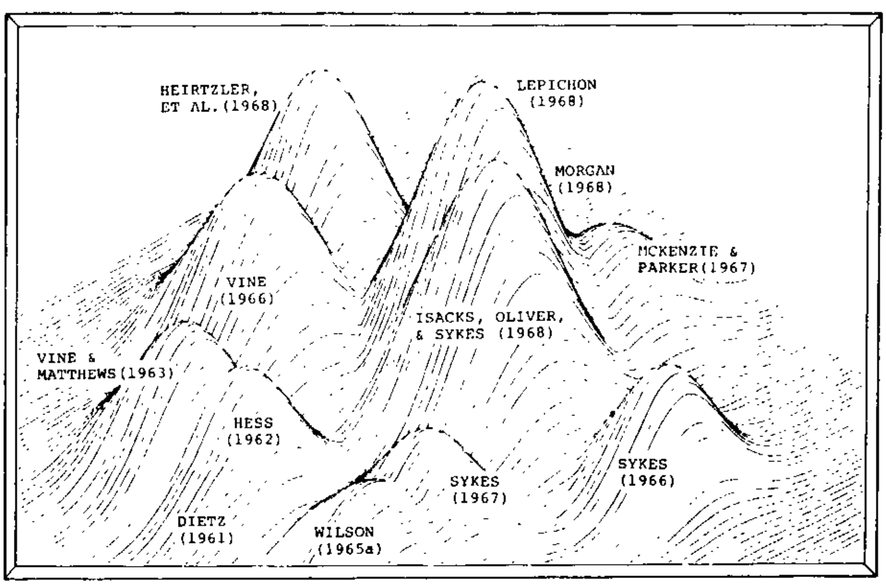

Figure 2 *Hill model for the 1970 plate tectonics cluster: 12 of 19 articles.*

inclusion in the picture. These other articles include the Oliver and Isacks (1967) study of the Tonga Trench and McKenzie and Morgan's (1969) analysis of triple junctions as well as Barazangi and Dorman (1969), Heirtzler (1968), Isacks and Molnar (1969), McKenzie (1969), and Pitman and Heirtzler (1966). In fact, if one lowers the clustering threshold from .16 to .10 in the normalized scores, then 62 references are included in the plate tectonics cluster. At this level of clustering many references are included that are less directly related to plate tectonics. Only nine of these other references - a petrology group - constitute a cluster of four or more references when the threshold is at .16 in the normalized scores.

The petrology and geochemistry group of articles is portrayed in Figure 3. These articles are concerned with developing models of the origins of igneous rocks using high temperature and pressure laboratory data on synthetic and natural rocks. The major application of this work is how different types of oceanic basalts could be derived from the same magma source in the mantle. (The Yoder and Tilley (1962) article is one of the classics; it was cited 55 times in 1970.) The article by Gast (1968) is distinctive because it emphasizes the distribution of the trace elements and its results are related to sea-floor spreading processes occurring at mid-ocean ridges. In addition to the other references shown in Figure 3, articles by Melson *et al.* (1968), O'Hara (1965), and van Andel and Bowin (1968) are in this cluster.

Figure 4 shows the relative location of the different clusters produced by the co-citation analysis for 1973. By this time the petrology and geochemistry group had separated into two clusters: a petrology group organized around the Yoder and Tilley (1962) and Green and Ringwood (1967) studies of basaltic rocks and a trace-element cluster organized around Gast (1968). In 1973 the classic papers on plate tectonics form a separate and fairly small cluster, which is portrayed in Figure 5. (LePichon (1968) was cited 75 times in 1973.) It is interesting to note that the major sea-floor spreading articles, such as Hess (1962), Vine (1966), and Heirtzler *et al.* (1968), are not retrived by co-citation analysis in 1973 with a normalized threshold of .16, even though these articles are cited frequently in this year. There are two possible explanations. First, the sea-floor spreading hypothesis was quickly incorporated in the broader theory of plate tectonics. Second, the studies that continued to map linear magnetic anomalies and calculate spreading rates focused on spe-

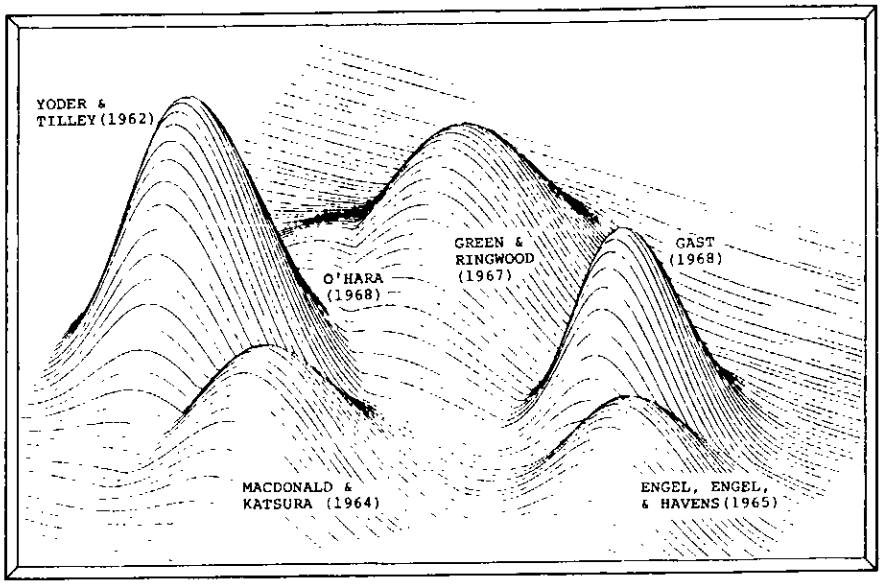

Figure 3 *Hill model for the 1970 petrology cluster: 6 of 9 articles.*

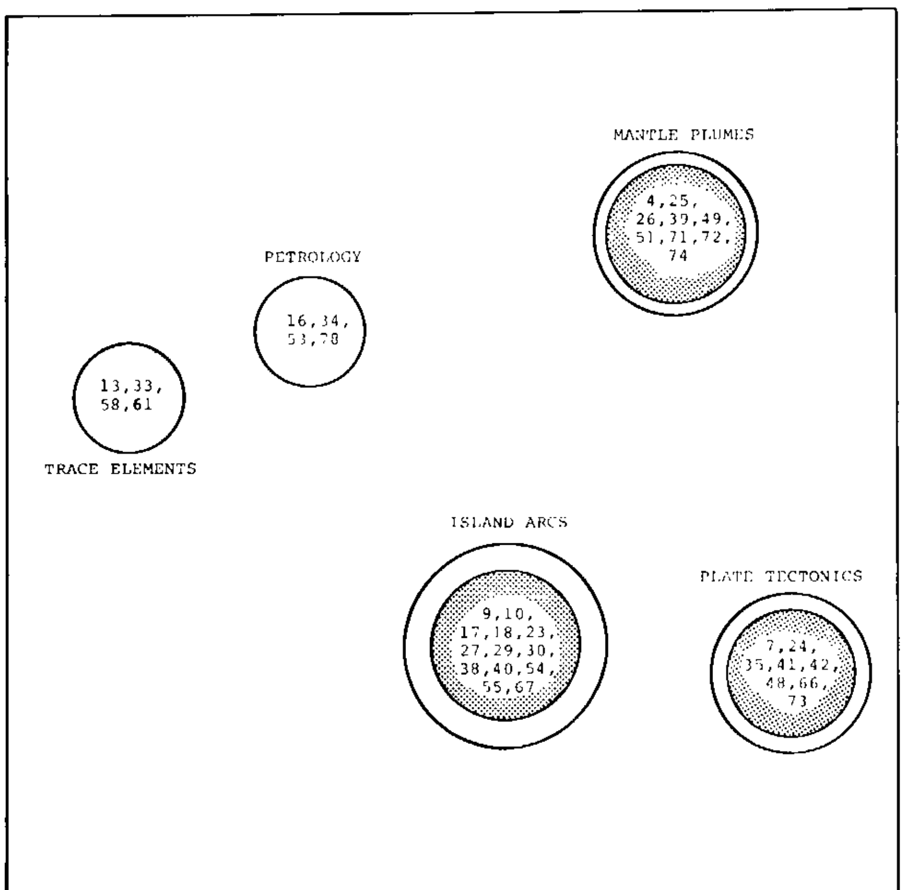

Figure 4 *Relative locations, sizes, and articles for the five major clusters in 1973. The areas of the circles are proportional to the number of articles in the clusters and the shaded areas represent the number of articles used to construct the hill figures. The reference numbers for all the articles in the cluster are given inside each circle.*

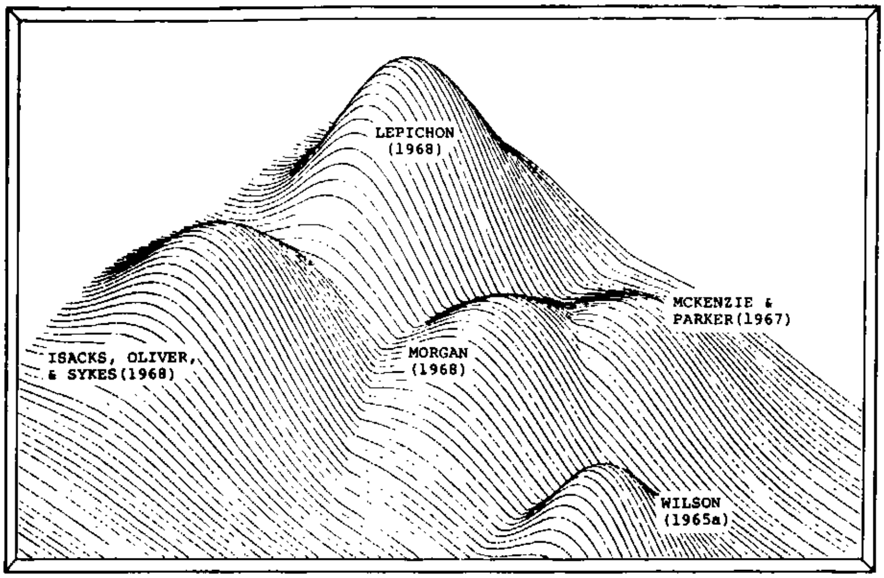

Figure 5 *Hill model for the 1973 plate tectonics cluster: 5 of 8 articles. See Figure 4 for identification of all the articles in this cluster.*

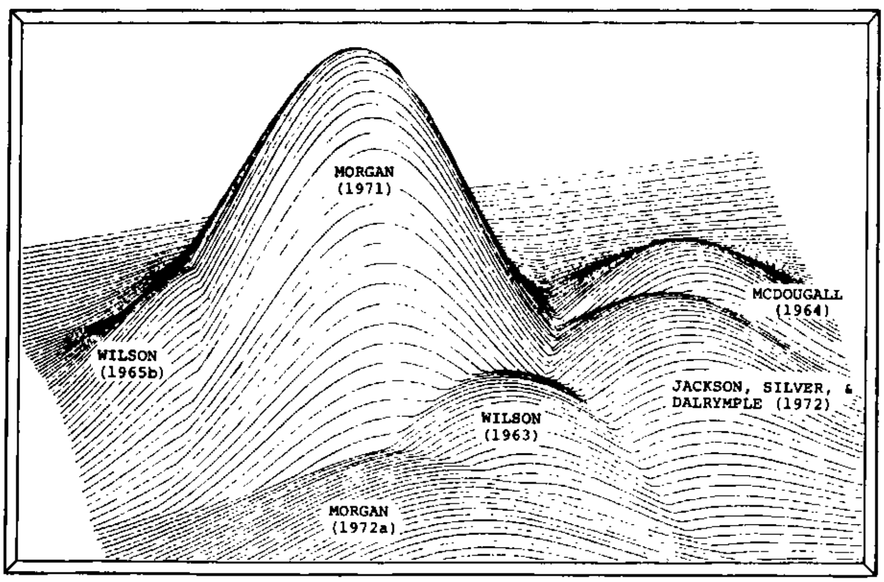

Figure 6 *Hill model for the 1973 mantle plumes cluster: 6 of 10 articles. See Figure 4 for identification of all the articles in this cluster.*

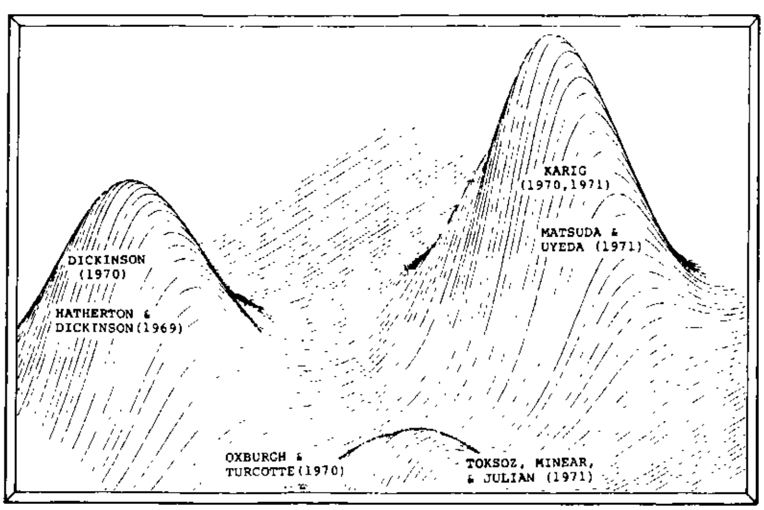

Figure 7 *Hill model for the 1973 island arcs cluster: 7 of 13 articles. See Figure 4 for identification of all the articles in this cluster.*

cific oceans and tended to cite previous studies for these areas. Thus, the classic papers in sea-floor spreading may remain highly cited, but not co-cited enough with other major articles to be retrieved at the .16 level.

The most interesting cluster for 1973 is a new one dealing with mantle plumes or "hot spots", which is portrayed in Figure 6. The original articles by Wilson (1963, 1965b) proposed that linear island chains like the Hawaiian Islands were formed as a plate moved over a stationary hot spot in the mantle. Morgan developed this mechanism in several articles that considered different island chains and suggested that hot plumes of material from the lower mantle provided the heat source for the hot spots and the driving force behind plate motions. The Wilson (1963), McDougall (1964), and Jackson *et al.* (1972) articles are concerned specifically with the Hawaiian Islands; the last article proposes an alternative explanation for the formation of such island chains. (For reference the Morgan (1971) article was cited 55 times in 1973.)

The other major cluster in 1973 consists of articles loosely related to island arcs; these articles form three somewhat separated groups within which the individual articles cannot be separately portrayed (see Figure 7). The Matsuda and Uyeda (1971) and Karig (1971a) articles are concerned with the geophysical characteristics and origins of "marginal basins," which form behind island arcs. They suggest that these basins are formed by sea-floor spreading processes. The Dickinson (1970) and Hatherton and

Dickinson (1969) articles deal with the relationship between the depth to the Benioff zones and the chemical composition of the volcanic rocks formed above the zone. The third group of articles (Oxburgh and Turcotte, 1970; Toksoz *et al.*, 1971) consider the thermal characteristics of the downgoing slab of lithosphere that forms the Benioff zones beneath island arcs. A fourth group of articles in the island arc cluster, but not portrayed in Figure 7, are on the driving mechanisms for plate motions, including McKenzie (1969) from the 1970 plate tectonics cluster. (The Karig (1971b) and Dickinson (1970) articles were both cited 32 times in 1973.) By 1975 each of these four groups in the 1973 island arcs cluster had separated or joined different clusters, while some of the other 1973 clusters had "drifted" together.

Figure 8 shows the relative positions and sizes of the major clusters in 1975. The largest cluster combines the classic plate tectonis articles with the mantle plumes cluster and some petrological studies of magma origins by Green (1971); see Figure 9. The articles providing the connecting "ridges" between these two subjects are by Morgan (1971) and Minster *et al.* (1974). The latter article is particularly interesting because it combines a new and more sophisticated analysis of the rotation pole locations using the linear magnetic anomalies and then tests whether these results are compatible with the trends and changes in trends of linear island chains, which indicate the location of hot spots. This match between the several sets of data supported the hypothesis that the hot spots were fixed relative to each other, presumably because they had deep mantle origins, and, therefore they may provide a fixed frame of reference for plotting plate motions. The Jackson articles, however, consider alternative explanations for linear island chains. This synthesis of plate tectonics and mantle plumes appears to have been short lived. Co-citation data for 1977 indicates that the major articles by Morgan no longer form the core of a cluster. (LePichon (1968) was cited 38 times in 1975.)

A new cluster of articles in 1975 represents the first major application of plate tectonics to continental geology. These articles, which are represented in Figure 10, are concerned with ophiolites. They consider the evidence and possible mechanisms within the plate tectonics framework for the emplacement of large areas of the ocean floors along the edges of continents by collisions between continents or island arcs. One of the explanations for ophiolites given by Dewey and Bird (1971) and Coleman (1971) is

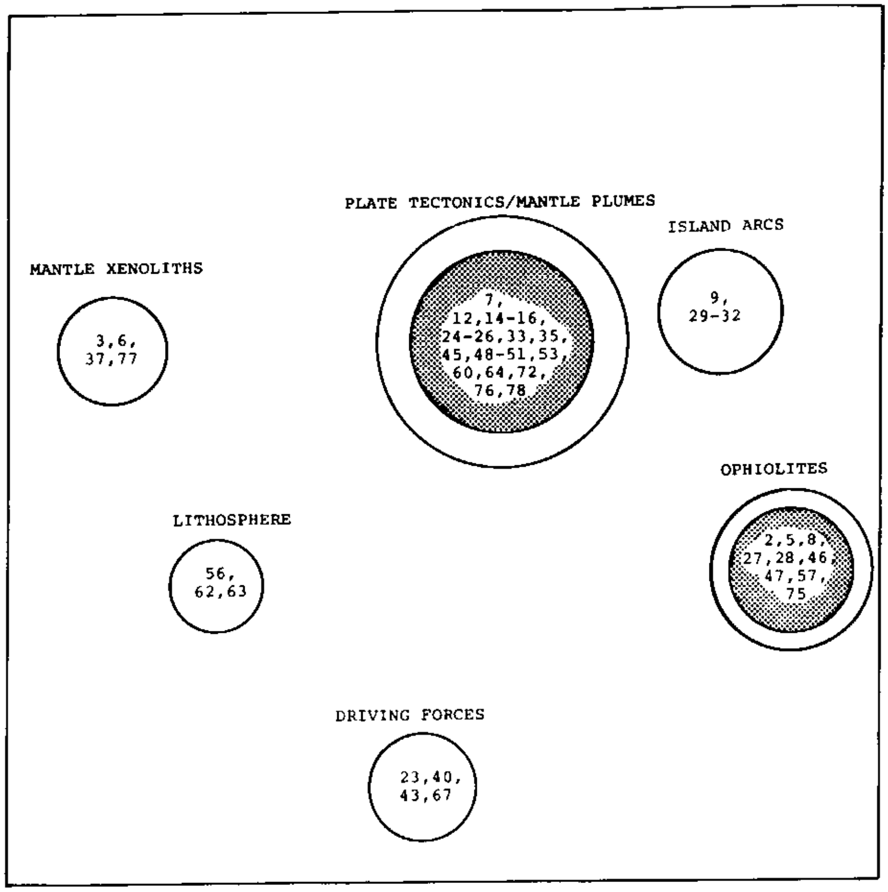

Figure 8 *Relative locations, sizes, and articles for the six major clusters in 1975. The areas of the circles are proportional to the number of articles in the clusters and the shaded areas represent the number of articles used to construct the hill figures. The reference numbers for all the articles in the cluster are given inside each circle.*

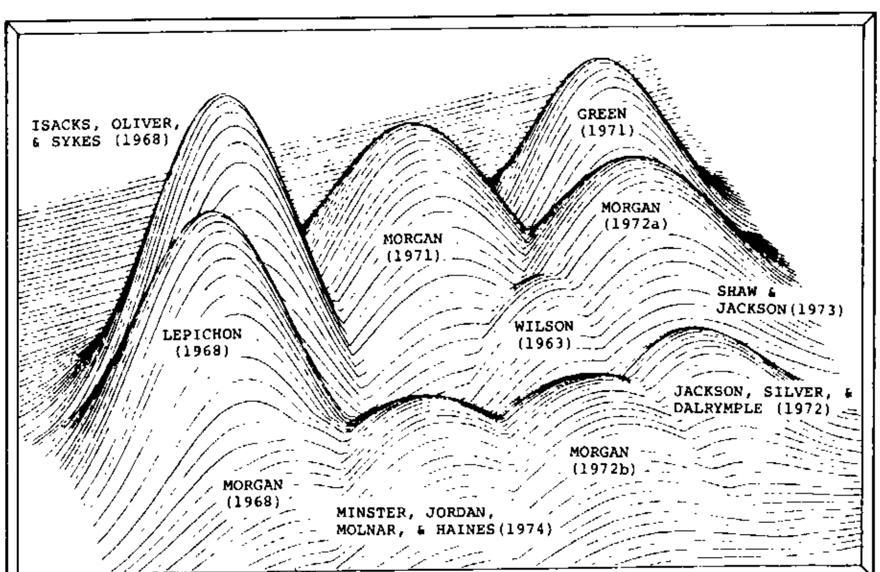

Figure 9 *Hill model for the 1975 plate tectonics/mantle plumes cluster: 11 of 21 articles. See Figure 8 for identification of all the articles in this cluster.*

that sometimes parts of the ocean floor are not subducted down the trench, but may be "obducted" onto the continental margin, i.e., thrust over the edge of the continent instead of under it. The Miyashiro (1973) and Moores and Vine (1971) articles, while differing in their proposed plate tectonics mechanism, consider evidence that parts of Cyprus are composed of such oceanic crust. The Pearce and Cann (1973) article provides geochemical means of determining what kinds of tectonic mechanisms emplaced a given ophiolite sample. (The Dewey and Bird (1971) article was cited 30 times in 1975.)

The three other major clusters for 1975 in Figure 8 also are related to plate tectonics, but separate hill figures are not provided. The island arc cluster consists of four articles by Karig on the structure and evolution of island arcs and their marginal basins. The Dickinson (1970) article is also in this cluster. The lithosphere cluster is composed of three articles dealing with the elevation and heat flow of oceanic plates. The driving force cluster combines articles on mantle convection currents and characteristics of the lithospheric plates in Benioff zones, including the Toksoz, *et al.* (1971) article, which was previously in the loosely connected 1973 island arc cluster. Finally, the mantle xenoliths cluster is composed of articles that attempt to reconstruct the characteristics of the upper mantle by the petrological analysis of these inclusions. This cluster is less directly related to plate tectonics, but one of the articles in the cluster by Boyd (1973) attempts to relate characteristics of xenoliths in the diamond-bearing kimberlite pipes of South Africa to the separation of Africa from South America. As can be seen in Figure 8 this cluster is relatively removed from the other clusters more directly related to plate tectonics.

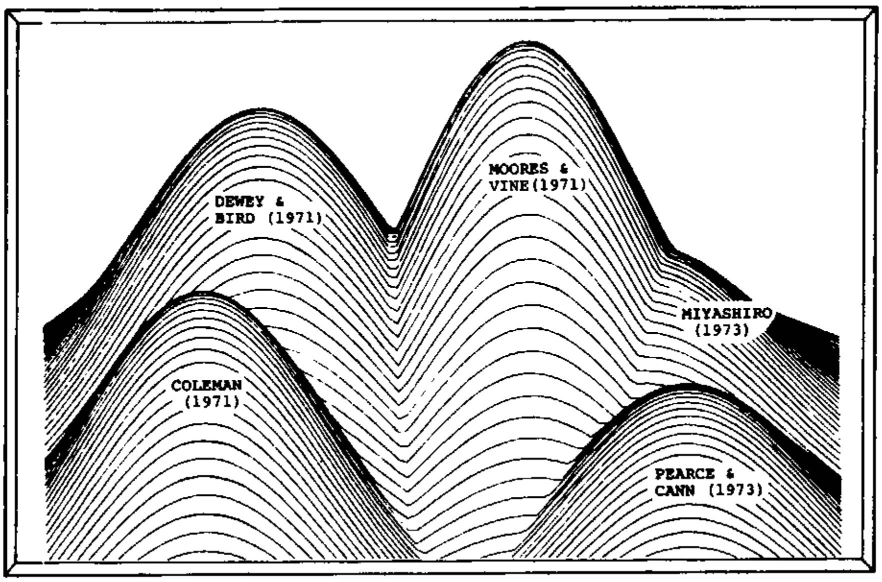

Figure 10 *Hill model for the 1975 ophiolites cluster: 5 of 9 articles. See Figure 8 for identification of all the articles in this cluster.*

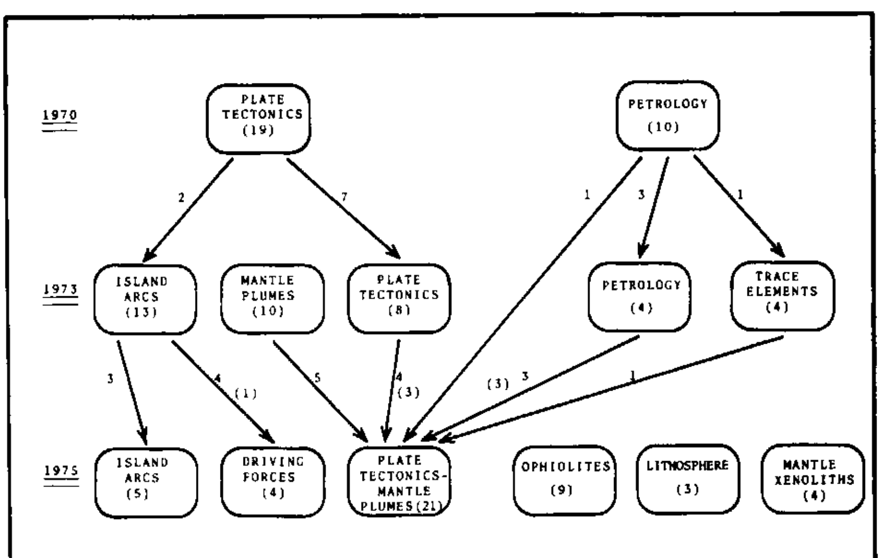

Figure 11 *Patterns of article movements among the major clusters for 1970, 1973, and 1975. The numbers in the boxes show the number of articles in the clusters defined with a threshold of .16 for the normalized scores. The numbers along arrows indicate how many articles moved between or remained in clusters between years; those in parentheses indicate how many of the 1970 articles carried over to 1973 were also carried over to 1975.*

Figure 11 summarizes some of the movement of articles between different clusters by showing the major clusters for the given years and the continuity of articles between clusters. Except for the mantle xenoliths cluster, the major clusters that appear for the first time in a given year are derived from smaller clusters in earlier or intervening years. Thus, there is more continuity than represented in this figure.

Conclusion

This article has reported the results of the application of co-citation analysis to map an area of science that is experiencing rapid conceptual evolution. It appears that 11 citing years ago a plate tectonics continent and a smaller petrology continent existed near each other. Within three cy there was considerable fragmentation, erosion, drift, and genesis of new continents. A trace element fragment drifted away from the petrology continent. The sea-floor spreading margins of the plate tectonics continent eroded away, while the island arcs (and driving forces) fragment drifted away and grew in size. Most impressive, however, was the rapid development of a new continent over a mantle hot spot.

Fragmentation, drift, and creation continued over the next two cy. Most important was the continental collision between the plate tectonics, mantle plumes, and fragments of the petrology and trace elements continents. The loosely connected island arcs continent rifted into fragments concerned with marginal basins and driving forces. During this two cy period some of the smaller continents (ophiolites and lithosphere) grew larger and more important. Mantle processes continued to play a role and helped form the xenolith continent.

The maps of these conceptual continents illustrate that co-citation analysis may be a useful tool for historians and sociologists of science, although some question its usefulness as a source of information about the cognitive organization and change within a scientific discipline (cf., Edge, 1979). The assessment of the validity of the above results must be based on the opinions of the scientists whose citation patterns provided the initial input for the co-citation analyses. If the above results are correct, it appears that the frontier of the geological sciences is an area of rapid and exciting movement.

Acknowledgements
The first author would like to dedicate this article to the geoscientists who consented to interviews for his dissertation research on the development of plate tectonics (Stewart, 1979), which will be published by Academic Press in 1982.

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