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A Citation Network Analysis of Lithic Microwear Research

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ABSTRACT

The introduction of lithic microwear research into the wider archaeological community by Keeley (1980) was concurrent with the development of the processual paradigm and the adoption of the scientific method. Subsequently, lithic microwear research has benefited from over 35 years of innovation, including the introduction of novel methodological and analytical procedures. The present study employs a citation network to objectively analyse the development of microwear research. Given developments in technology, as well as the institutional isolation of early microwear research, the present analysis considers the citation network that stems from Keeley's seminal 1980 volume . The 363 papers identified as having cited Keeley (1980) in the subsequent 35 years were treated as individual nodes within the citation network. Before analysis, nodes were assigned attributes, including the type of research published and whether they were supportive of three key aspects of Keeley's experimental program: the ability to determine the function of the tool and to ascertain the type of worked material from microwear, as well as the use of high-powered microscopy techniques. Emergent properties of the papers, including closeness centrality, indegree and betweenness centrality, are used to test for significant differences between paper attributes. Similarly a clustering algorithm is used to objectively define distinct clusters of important papers within the discipline. Results indicate that a small number of nodes in the network maintain statistically significant influence on the form of the citation network. These important nodes and the distinct 'schools of thought' identified are discussed in the context of Keeley's initial contribution to the sub-field.

Keywords: graph theory; use-wear analysis; traceology; processualism; archaeological theory

1. Introduction

The advent of processual archaeology in the 1960's (Binford and Binford, 1968; Clarke, 1973) marked the adoption of progressively scientific methods within archaeological research. The timing of this shift to include more quantitative methods closely aligns with the development of lithic microwear analysis as a sub-field of archaeological research. In turn, lithic microwear research offers a rare opportunity to examine how a sub-field's accepted knowledge developed in context of the wider adoption of the scientific method. Although many of the key ideas of lithic microwear research were originally conceived of by Semenov (1957) in the 1950's, its introduction into the wider academic community would not occur until the 1960's (Semenov, 1964), developing through the 1970's (Tringham, 1974; Keeley, 1974; Odell, 1975; Hayden, 1979) and resulting in its establishment as a paradigm (sensu Kuhn, 1962) in the 1980's subsequent to Keeley's seminal volume (Keeley, 1980). An excellent review of this development was conducted by Stemp et al. (2015) who note that Keeley (1980) was motivated to publish, at least in part, by what he viewed as the limited applications of Semenov's original methods in the 1970's. Further, immediately subsequent to this period the introduction of high-powered microscopy marked the beginning of a trend of increasingly sophisticated metrological and tribological instruments utilised by the sub-field (Stemp et al., 2015). Perhaps as a result of the proliferation of these technologies, as well as the continued use of expert qualitative analysis, many methodologies currently exist within microwear studies and there have been calls for standardisation (Evans et al., 2014; Van Gijn, 2014). Yet, in some form, microwear analysis is replete in the literature as it is often included in site reports and therefore can be considered a substantive sub-field.

In the spirit of "critical self-consciousness" (Clarke, 1973:7), synonymous with processual archaeology, a citation network analysis of lithic microwear studies is employed here to objectively assess the development of three key ideas in this sub-field. Several other fields have engaged in critical, reflexive analysis, including medicine (Greenberg, 2009, 2011), ecology (Barto and Riollig, 2012) and genetics (Voracek, 2014). These studies have all employed citation network analysis, which applies established mathematical graph theory to the network of citations connecting articles that comprise the core of accepted knowledge in a given discipline. The development of common knowledge in a field involves many other materials and processes including: books, conference discussion, posters, interpersonal interactions and, increasingly, content on social media. However, peer-reviewed journal articles are a detailed, standardised record of academic discourse, which can be used to distinguish accepted knowledge at the core of a field from more contentious ideas, and are amenable to network analysis. This method is particularly advantageous as it is largely objective, requires few initial assumptions, and is increasingly practical with the availability of platforms to conduct it.

We consider the distribution of papers that find evidence for and against three central tenets of Keeley's (1980) experimental microwear program; "…that with the use of high magnification…one can almost always isolate the used portion of the tool and reconstruct its movement during use, as well as, in the majority of cases, determine exactly which material was being worked" (Ibid.:78). Specifically we assess support for: the use of high-powered microscopy methods within microwear research, and the use of this method to determine both tool function and the type of worked material. Since worked material and implement function determination are based on identifying the used portion of a tool, as described by Keeley above, we do not focus on this latter aspect of his work. The present analysis makes no comment on the efficacy or suitability of microwear analysis or its methodologies but instead asks to what extent the sub-field is still characterised by Keeley's (1980) formative ideas. The network is predicted to be mostly supportive of these ideas since they initially defined the sub-field. Similarly, types of paper and their position in the network are also analysed to identify the most influential types of papers in the sub-field. Review papers are predicted to be the most influential type of paper since they draw together the current state of the field at the time of publishing and are often referenced as primer for the reader of original research articles. Finally, emergent properties of the network and sub-clusters within it are analysed in an effort to identify distinct 'schools of thought' within the discipline.

2. METHODS

2.1 Node Selection

Given developments in technology, as well as the political isolation of early studies in the field, the present analysis considers the citation network that stems from Keeley's 1980 volume. A list of potential papers that could be in the citation network was drawn from journal articles that cited Keeley (1980) and were published in the subsequent 35 years to May 2015. From these papers only those which concerned microwear in some way and were written in English were validated as nodes in the network.

Only English language papers were validated as broadening this selection criteria would likely result in strong language barriers obscuring more subtle structural variation, analysed here to chart the development of key ideas in the discipline. Works preceding Keeley (1980) were not included in the analysis as, although they may reveal much about the establishment of microwear as a sub-field in the western archaeological literature, they are much fewer in number than those that succeed it and were not written when the sub-field was established per se. It would, for example, be inappropriate to categorise these early articles as being supportive of a central idea of the sub-field before this paradigm was formalised in the literature.

To sample the relevant literature other citation network studies have used indexed databases of research articles, such as Scopus or PubMed. In the case of archaeology, which has many out-of-publication titles, these databases may not cover the same amount of literature as Google Scholar (Google Inc., 2015), and so this non-indexed database was used. Book chapters are omitted from the present analysis as they are not always available online and so were not compatible with the data collection method used here. Further the availability of printed resources and the potential lack of a peer review process for book chapters may introduce additional variation to the citation network from this distinct publishing process. It would be of interest to extend this analysis to book chapters and non-English language research in the future, but it is beyond the scope of this paper. It could be argued that, as the network is a snapshot of the sub-field in 2015, any papers with a high number of citations are simply the beneficiaries of time. Certainly, the longer something has been part of the literature, the greater the likelihood it has been cited. This would, however, be the case at any cut-off period and controlling for the effects of time by weighting citations may artificially distort the structure of the network in unforeseeable ways. Nevertheless, this potential effect of published year is noted in the discussion.

The 363 validated papers were then treated as nodes in the network and each was assigned several attributes separately by authors AK and CD. In rare cases of discrepancy each was re-evaluated. Papers were first categorised as independently supportive, neutral or unsupportive of three key aspects Keeley's (1980) model: the ability to determine the function of the tool and determine the type of worked material from microwear traces, as well as the use of high-powered microscopy methods. Direct quotes reflecting these respective views from each paper are given in Supplementary Information 1. The criteria used to assign a support categorisation for each variable are given in Table 1. Each paper was also assigned a type dependent on the main academic focus of the work (Table 2).

Aspect of Keeley's (1980) model	Supportive	Neutral	Unsupportive
The use of high-power microscopy methods	The article applies or tests high-power microscopy and finds it satisfactory or otherwise states it is effective for microwear analysis following Keeley (1980).	The article cites Keeley’s seminal role in developing this methodology but does not apply or test it, nor comment on its efficacy.	The article uses only a low power/ non-microscopy approach or finds Keeley’s (1980) high-power approach is not effective for microwear analysis in some way.
The function of tools can be visually identified from microwear	The article states that the function of an implement can be identified from microwear traces following Keeley (1980). This may be a reference, a test of the method or its application to material.	The article is equivocal on whether function can be identified from microwear traces using Keeley’s methods or does not make reference to this idea.	The article holds that the function of an implement cannot be reliably inferred from microwear traces following Keeley (1980). This may be a reference, a test of the method or its application to material.
Type of worked material can be visually identified from microwear	The article states that the type worked material an implement was used on, can be identified from microwear traces following Keeley (1980). This may be a reference, a test of the method or its application to material.	The article is equivocal on whether worked material can be identified from microwear traces using Keeley’s methods or does not make reference to this idea.	The article holds that the worked material of an implement cannot be reliably inferred from microwear traces following Keeley (1980). This may be a reference, a test of the method or its application to material.

Table 1: Definitions of support for the three key aspects of Keeley’s model analysed here.

Type of Paper	Definition
EMR – Experimental Microwear Research	Published research examining an aspect of lithic microwear theory through experimental means.
AA – Assemblage Analysis	Publications applying microwear analysis techniques/methods to the analysis of lithic artefacts with the intention of inferring information relating to the tool’s use.
R - Review	Review publication focussing upon aspects of lithic microwear research (including its reliability, developmental mechanics, application to artefacts etc.)
OF – Other Focus	Publications that cite Keeley (1980) but are not specifically focussed upon lithic microwear research. Includes microwear research which is not focussed upon lithic artefacts (e.g. bone tools, or landscape use).

Table 2: Definitions of paper types according to the main research focus of the published work.

2.2 Network Creation

In order to build the network connections between nodes each citation was treated as a directed edge. The edges were directed since papers could not cite future literature and therefore information could only pass through the network in a directed manner. In order to compute all the edges in the network the reference or bibliography section from papers was either gathered manually as an unformatted text file or, where possible, as a standardised .ris file. Due to natural language inconsistencies across reference lists in papers (such as abbreviations or the inclusion of special characters), a natural language processing algorithm written in Python 2.7.13 (van Rossum and Drake, 1995) by BP was used to extract occurrences of paper titles in these reference lists. From this newly structured data, a graph could be generated by assigning directed edges from title papers (sources) to cited papers (targets). In order to control for Type 1 errors, matching titles were evaluated for percentage character similarity and any above 80% were manually verified as either a correct citation or a similar but different paper. This was important for papers that discussed sites with special characters in their name that could be transliterated differently depending on the formatting. Further some important papers in the field contain ‘nested titles’ that contain the full title of another paper preceded by something akin to “a reply to” or suffixed by “in context”. Since these titles were longer, the exact character match only represented a percentage of the full title and manual verification was able to eliminate incorrect citations of similarly worded paper titles. Finally where papers appeared to reference each other reflexively this was manually verified (see results). This process generated a network containing 1132 citations.

2.3 Network Visualisation and Analysis

The network was visualised in Cytoscape 3.4.0 (Shannon et al., 2003), an open source software with a library of plug-ins capable of performing network analysis. Global and nodal network statistics are used to describe the network and were generated using the Networkx module for Python (Hagberg et al., 2008).

Perhaps the simplest way to assess the importance of papers is by how many times they are cited; their indegree. Here, indegree was normalized by dividing a node’s (x) indegree (i) by the number of nodes in the network (n) minus 1, since a paper cannot cite itself.

$$C_i(x) = \frac{i}{\mathrm{n} - 1}$$

Indegree, however, lacks any positional information about the node in the wider graph. A high indegree paper could be cited many times by papers who are not themselves cited and are at the extremities of the graph, or by many of the papers at the centre of the graph which are in-turn referenced by many others. Closeness centrality (C_c) conversely, describes how close the node is to the centre of the network. It is calculated as the average of the length of the shortest paths (d) between the node(x) and each of the other nodes (y) in the network. A higher closeness centrality value indicates a work cites or is cited by many other papers (Bavelas, 1950; Opsahl et al., 2010). In a sense, closeness centrality is a measure of how quickly ideas can spread through the sub-field, here represented as the network, rather than how often the given paper’s ideas are cited.

$$C_c(x) = \frac{n-1}{\sum_{b=1}^{n-1} d(x,y)}$$

Together indegree and closeness centrality capture much of the information in the network but are based on the number of connections each node has with little emphasis on the importance of these connections. Betweenness centrality (C_b) instead reflects the importance of a given paper in controlling the flow of information around a network. This measure of centrality is calculated by averaging the number of times the node in question (x) lies on the shortest path between each pair of nodes (y, z) in the network (Freeman, 1978; Brandes, 2001). A paper with high betweenness centrality indicates that it is an important ‘bridge’ for information to flow between otherwise less connected parts of the network.

$$C_b(x) = \frac{\sum y \neq x \neq z \left(\frac{(y,z)\ |x}{(y,z)} \right)}{\frac{1}{(n-1)(n-2)}}$$

Kruskal-wallis tests with post-hoc, Bonferroni corrected, Mann-Whitney U tests were run in PAST (Hammer et al., 2001) to test for significant differences between in-degree, closeness centrality and betweenness centrality statistics of each support classification. The same approach is applied to the analysis of the type classifications of each paper. To investigate if distinct 'schools of thought' exist in the network MCODE plugin (Bader and Hogue, 2003) for Cytoscape was used to objectively find highly inter-connected clusters in the network. These clusters represent sub-networks that internally reference each other more than they do other parts of the network. In-turn these clusters are ranked so that the first cluster represents the core of the network. The parameters used were: a degree cut-off of 2, a node score cut-off of 0.2, a minimum K-core of 2 and the 'haircut' correction was applied, to remove nodes only connected to clusters by one citation (Ibid.).

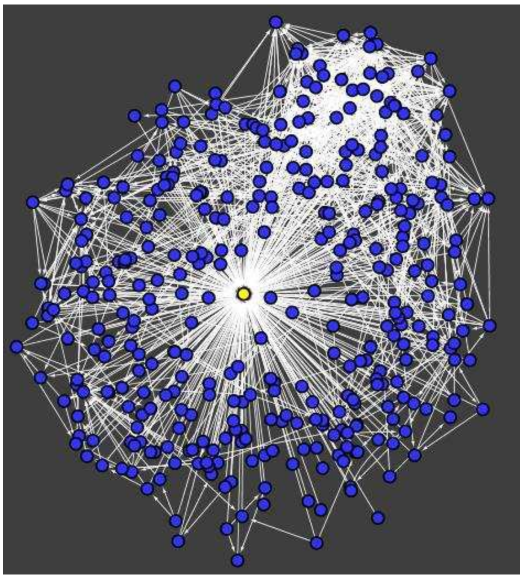


Figure 1: The network with Keeley (1980) added to the centre (yellow). Each blue dot represents one of the 363 validated papers that make up the network.

3. RESULTS

The network (Fig. 1) generated from the 363 validated papers is relatively small as the maximum distance from one paper to another is 10 citations (network diameter), yet it is also quite diffuse with a skewed distribution of indegree; some papers are heavily cited whilst many more are not cited within the network (Fig. 2). In two instances a pair of papers referenced each other as they were by the same authors and both in press in 1985-1986. Roughly one third of the papers (n = 129) were considered terminal nodes as they were not cited by any other paper in the network; i.e. displayed an outdegree of zero. Of these, around half (n= 64) only referenced Keeley (1980) and comprise a review paper (R), which mainly cites Japanese literature (Akoshima and Kanomata 2015), and other focus (OF) or assemblage analysis (AA) papers.

Of the 363 papers in the network only 9% were classified as unsupportive of the high-powered approach advocated by Keeley (1980) while 42% were neutral on the subject and 49% were supportive. Half of the papers in the network were supportive of Keeley's (1980) position that the function of an implement could be discerned from microwear, while 43% were neutral and just 7% were unsupportive. Similarly 45% of the articles analysed were supportive of the idea that worked material could be discerned via Keeley's (Ibid.) experimental program, while and 44% were neutral and 10% were unsupportive.

Due to the disparity of these sample sizes as well as significant deviations from normality, as tested via significant Shapiro-Wilk results, Kruskal-Wallis and Mann-Whitney U pairwise post-hoc tests were used to test for significant differences in network statistics between these groups. A Kruskal-Wallis of indegree between the categories of support for the high powered approach was significant (H = 6.289, p =0.0489) and post-hoc pairwise tests show this was the result of supportive papers being cited significantly, but only slightly, more often than neutral ones (p =0.0370). A Kruskal-Wallis of closeness centrality was significant (H= 6.637, p=0.0362) but after applying a Bonferroni correction there were no significant differences in network position between papers that differed in their support for the high-powered method. The same omnibus test revealed no significant differences in betweenness centrality between these support groups.

Conversely, article support for the determination of implement function via Keeley's (1980) microwear methodology did demonstrate significant differences in network statistics. Kruskal-Wallis tests of indegree (H= 8.93, p=0.0115), closeness (H= 11.28, p=0.0035) and betweenness centrality (H= 14.65, p=0.0007) were all significant and driven by significantly higher values for unsupportive articles than either neutral or supportive papers. Therefore it appears that, despite being a small part of the network, unsupportive papers are cited significantly more, are closer to the centre of the network and are more important in bridging the flow of information than either neutral or supportive papers (Fig 3).

Average indegree was significantly different when papers were grouped by their support for Keeley's (1980) claim that worked material can be discerned from microwear (H= 20.01, p< 0.001) as unsupportive papers were cited significantly more often than neutral or supportive papers. Closeness centrality showed a similar but more graduated pattern with significant differences (H= 6.487, p=0.0390) being driven solely by the fact that unsupportive papers were significantly more central in the network than supportive papers, while neutral papers had an intermediate value not significantly different from either other category. Betweenness centrality showed further significant contrasts (H= 14.65, p<0.001) due to significantly more important edges in the network passing through unsupportive papers as opposed to neutral or supportive papers with regard to the determination of worked material (Fig.3).

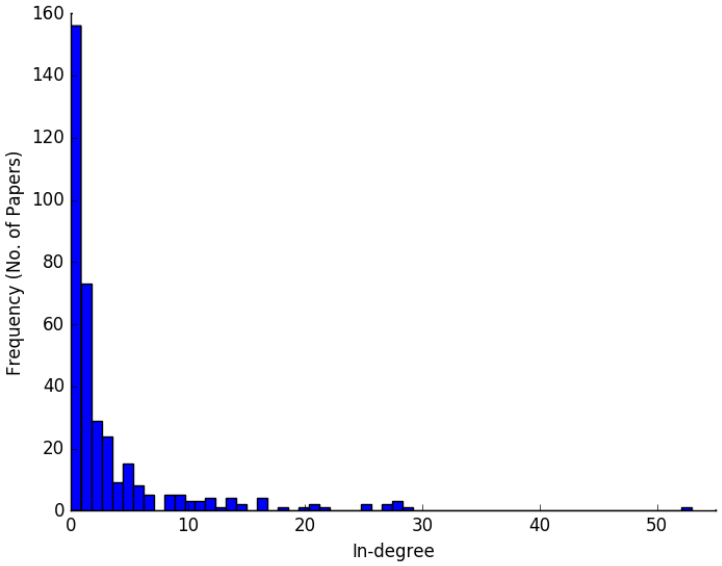


Figure 2: Histogram of the distribution of indegree in the network.

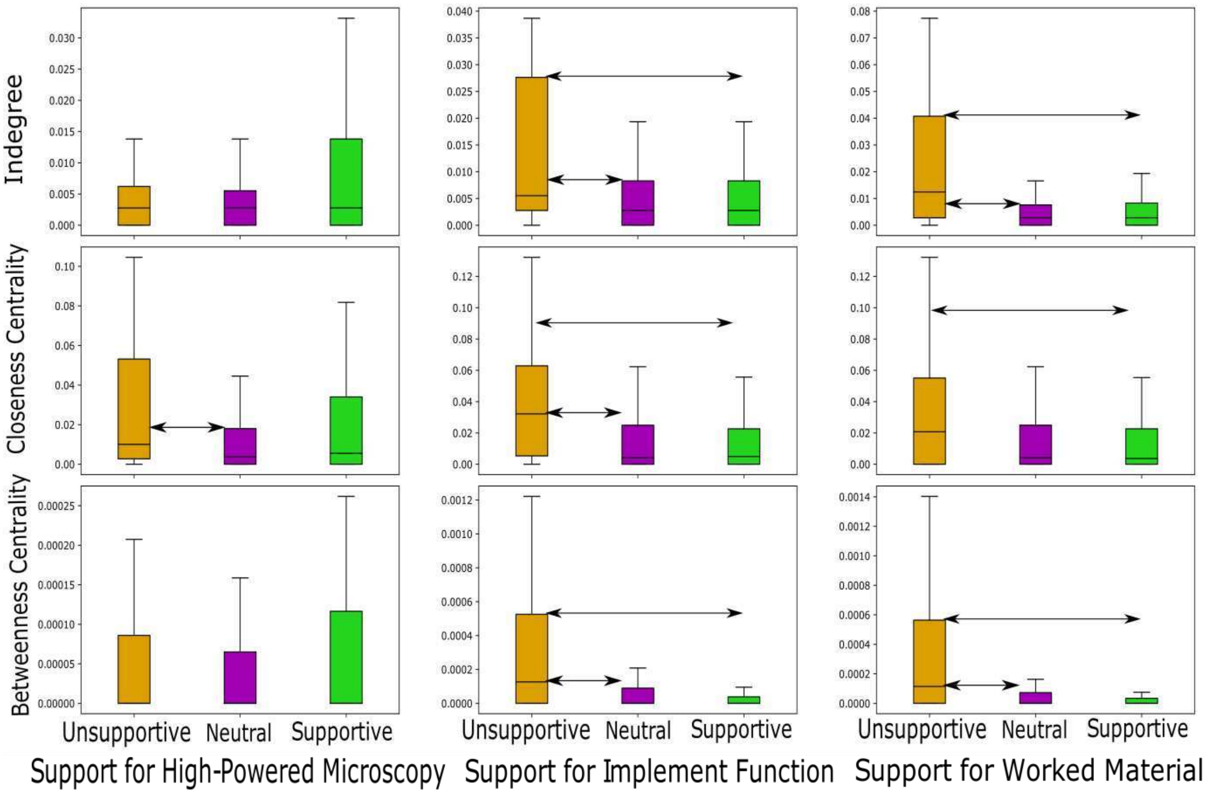


Figure 3: Boxplots of normalised average centrality measures by support of each of the examined aspects of Keeley's (1980) model. Significant differences, at p<0.05 subsequent to a Bonferroni correction, from post-hoc Mann-Whitney U pairwise comparisons are indicated by black arrows.

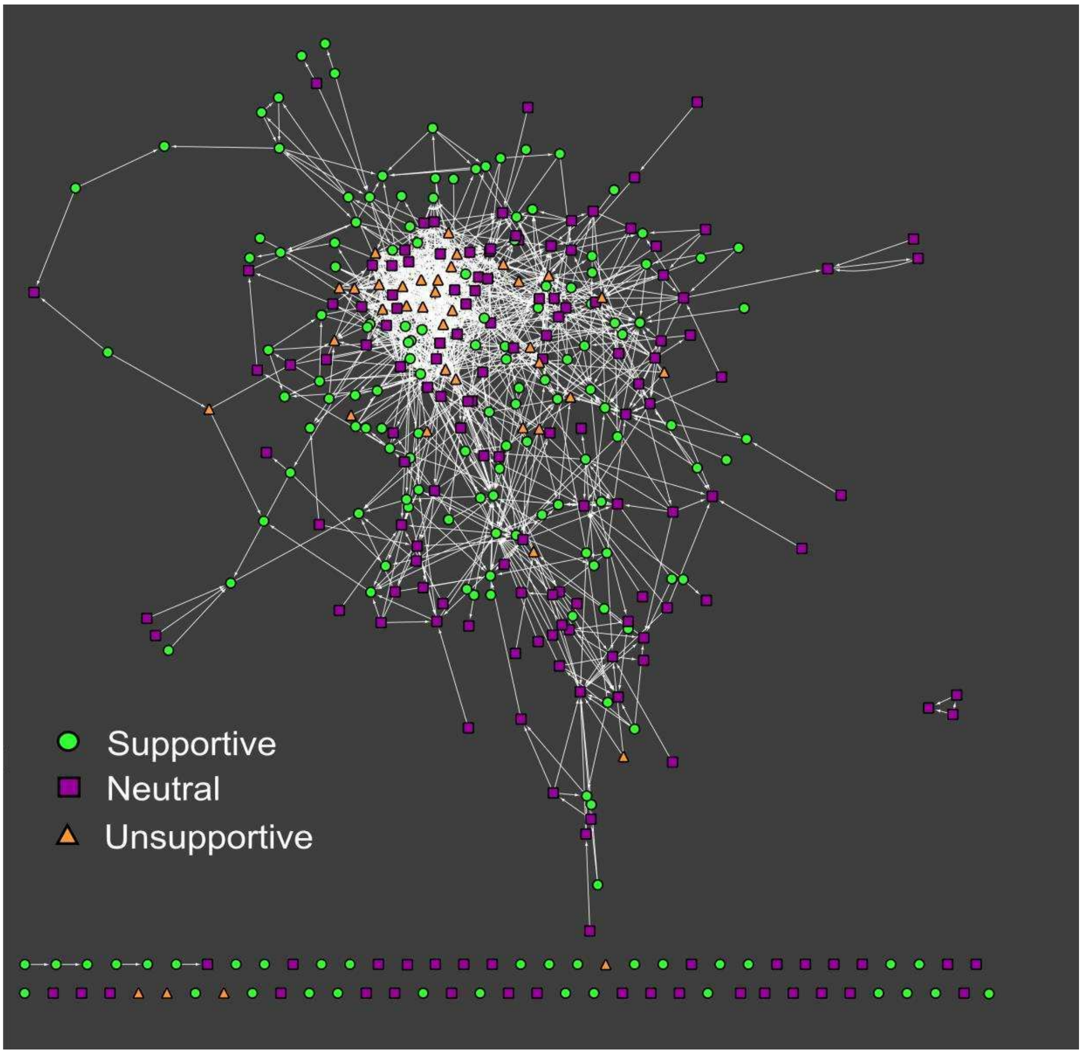


Figure 4: The network of 363 validated research papers with each node coloured by its support of Keeley's (1980) claim that worked material can be discerned from his microwear methodology. Nodes placed at the bottom of the figure represent papers that only cited Keeley (1980) and were not cited by other articles within the network.

3.1 Type

As can be seen in Figure 5, AA and OF papers comprise the 36% and 42% of the nodes in the graph, respectively, with Experimental Microwear Research (EMR) and R papers representing just 16% and 6%, each. Indegree comparisons demonstrated significant differences between the types of paper ($H = 87.22$, $p < .0001$). Specifically, the small number EMR and R papers showed a significantly higher number of citations than AA or OF papers, and while EMR did receive more citations this was not statistically distinguishable from R papers (Fig. 6). Closeness centrality also demonstrated significant differences ($H = 25.72$, $p < .0001$) between the types of paper with a clear separation of AA and OF papers from the EMR and R papers. However, here EMR papers closeness centrality was not significantly higher than AA, while R papers were slightly more central than EMR papers (Fig. 6). As hypothesised, betweenness centrality values were significantly higher for the R papers than other types ($H= 42.28$, $p < .0001$) though it was not significantly larger than EMR papers after the Bonferroni correction.

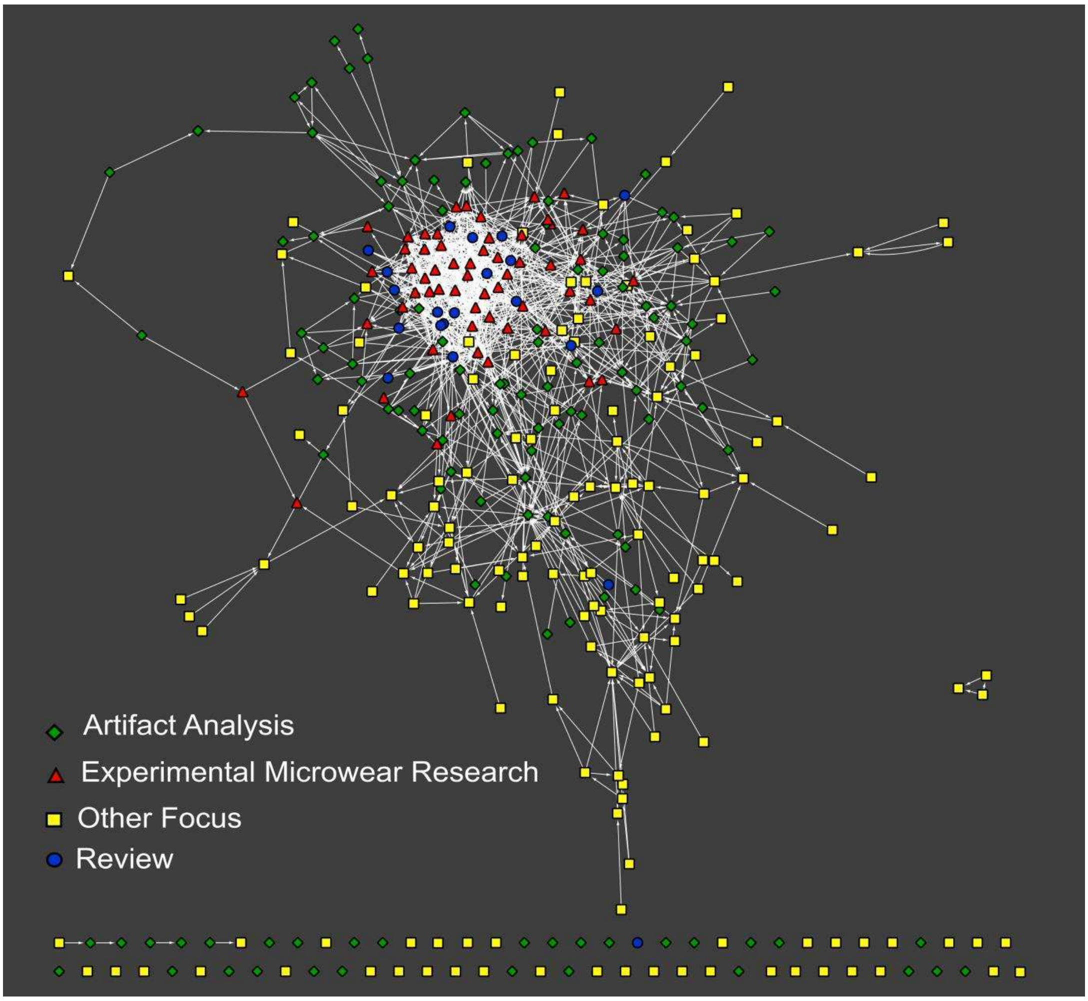
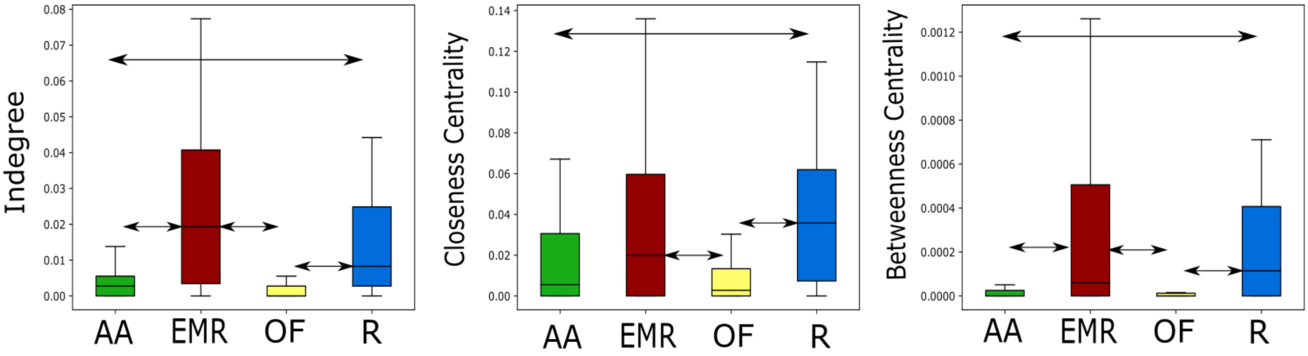


Figure 5: The network of 363 validated research papers with each node coloured by the type. Nodes placed at the bottom of the figure represent papers that only cited Keeley (1980) and were not cited by other articles within the network. Note that the core of the network is comprised of EMR and R papers.

Figure 6: Boxplots of normalised average centrality measures by article type. Significant differences, at $p<0.05$ subsequent to a Bonferroni correction, from post-hoc Mann-Whitney U pairwise comparisons are indicated by black arrows.



3.2 Cluster Analysis

Using standard parameters the MCODE algorithm was able to identify 10 unique sub-clusters within the network as visualised in Figures 7 and 8. The 71 nodes within these clusters represent ~20% of the total network and represent ~71% of the total citations in the entire network. The first two clusters represent the ‘core’ of the network with MCODE scores of 8.125 and 8, respectively, whereas clusters 3-10 have scores from 3.556 – 2.667. Clusters 5-10 represent specific concentrations; Cluster 10 comprises papers concerned with residue analysis and hafting (e.g.Dinnis et al., 2009), Cluster 9 represents several analyses by E.H. Moss (1983, 1986, 1987), Cluster 8 concerns ethnoarchaeology (Atherton, 1983; Agorsah, 1990; Cunningham, 2003), Cluster 7 represents papers concerning Paleo-Indian of North America by D.B. Bamforth (1985, 1986, 1991), Cluster 6 comprises 21st century papers on blind-testing as a methodology (Rots et al., 2006; Evans, 2014; Evans et al., 2014) and Cluster 5 mainly concerns Paleo-Indian bladelets (Yerkes, 1994; Kay and Mainfort, 2014; Miller, 2014, 2015). Cluster 4, containing 15 nodes, is dominated by assemblage analyses from the Levant, Africa and Europe but is also rooted in two papers that consider the effect of post-depositional and environmental factors on surface microwear (Sala, 1986; Burroni et al., 2002). Cluster 3 contains 16 nodes mostly focussed on quantifying microwear with microscopy and other processes that impact on the formation of microwear (Grace et al., 1985; Stemp et al., 2012; Lerner, 2014; Olle and Verges, 2014).

Cluster 2 only contains 9 nodes but comprises 23% of the citations in the network. This cluster is almost entirely EMR papers concerning metrology, quantification and the development of microwear using new microscopic methods (Stemp and Stemp, 2001, 2003; Evans and Macdonald, 2011; Borel et al., 2014; Key et al., 2015), although it also includes one of the oldest interferometry papers in the field (Dumont, 1982). Indeed, even the single AA paper in Cluster 2 employs atomic microscopy (Faulks et al., 2011). Cluster 1 is the core of the graph with 17 nodes and integral to 34% of the citations in the network. The papers in this cluster are all EMR and R papers, including those concerning the original debate over blind testing methodology from the 1980’s (Newcomer et al., 1986, 1988; Moss, 1987; Bamforth, 1988), as well as quantitative analyses and methodological testing papers (Stemp et al., 2008, 2009, 2010 ,2014; Evans and Donahue, 2005; Evans et al., 2014). Both Clusters 1 and 2 have articles mostly unsupportive (56%) of Keeley’s (1980) assertion that worked material can be identified from microwear in contrast to all of the other identified clusters (Fig.8). For the determination of implement function Cluster 2 has one more neutral than for worked material but is otherwise the same. Conversely, Cluster 1 is predominantly neutral for implement function with less unsupportive papers (30%) and one further supportive article than the two for worked material.

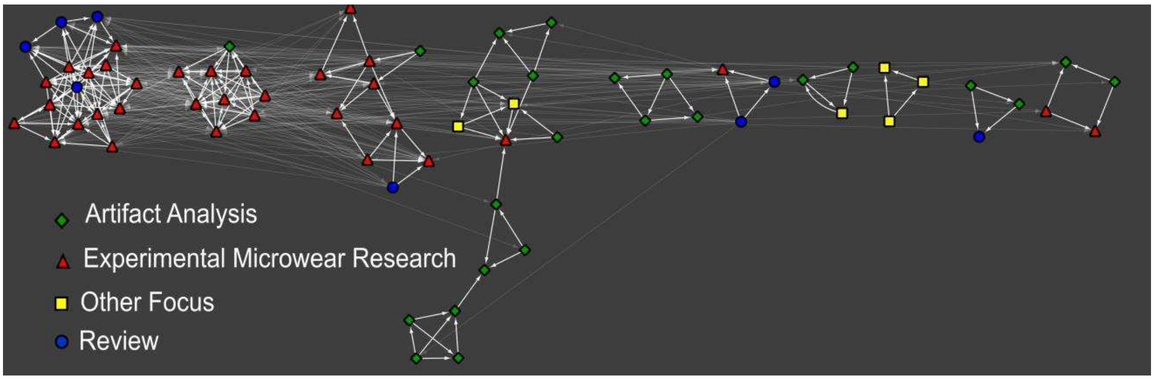


Figure 7: The 10 sub-clusters of the graph identified by the MCODE module, coloured by paper type and ordered by the most central sub-cluster to the least central, from left to right. Citations within networks are represented by solid white lines whereas citations between clusters are represented as thin grey lines.

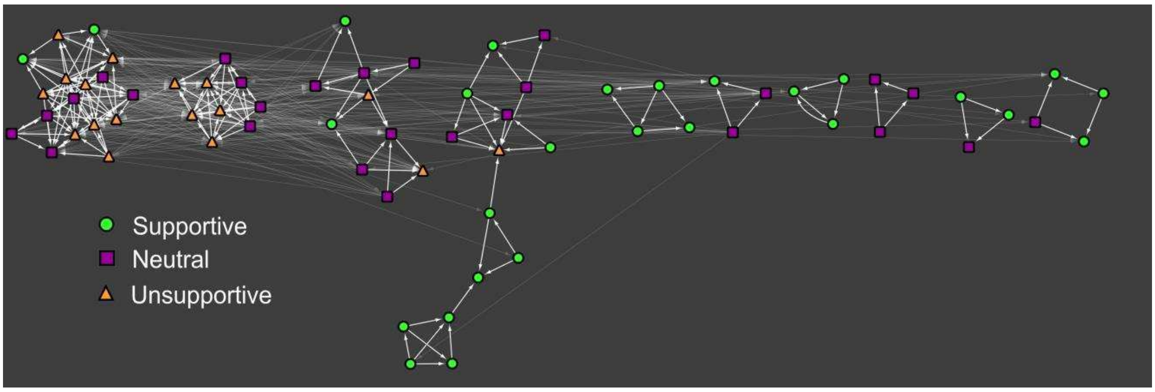


Figure 8: The 10 sub-clusters ascending from left to right of the graph identified by the MCODE module, as in Figure 7, but coloured by support of the identification of worked material. Note the preponderance of supportive (green circles) papers to the right and unsupportive (orange triangles) to the left.

4. DISCUSSION

The Network

The aim of this paper was to analyse the development of common or accepted knowledge in lithic microwear analysis research from its establishment by Keeley in 1980 as expressed in an objectively created network of citations. With this retroactive snapshot of the field in 2015 it was possible to test to what extent Keeley's (1980) experimental microwear program still characterises the sub-field.

It is clear from the structure of the network that there is a central core of papers that form the nucleus of the sub-field and a relatively large periphery of papers that only cite a few others in the network (Figs. 1, 2, 4, and 5). This disparity in connectivity is perhaps clearest in Figures 4 and 5 where ~17% of the papers only cite Keeley (1980) or each other and would not be in the network but for this definition of the sub-field. The skewed distribution of connectivity indicates a structure of the citation network in which there are some particularly influential papers. While it is true that papers published in 2015 are less likely to be cited as often, the 10 most cited papers span 1982-2008 indicating this structure is not simply a function of time.

Support

High-powered microscopy is central to Keeley's (1980) program and is perhaps one of the clearest aspects in which his work departs from earlier studies such as Semenov (1964). In terms of number of papers, the network was 49% neutral and 42% supportive of this aspect of Keeley's work. While not statistically significant, supportive papers, that largely employed the technique for assemblage analysis, were cited more often in the network than neutral or unsupportive articles (Fig.3). The only significant difference regarding high-powered microscopy was that unsupportive papers were closer to the centre of network that neutral papers, though not more so that supportive ones. Unsupportive papers constituted older papers that applied a low-power approach (e.g. Stafford and Stafford, 1983, Kenmotsu, 1990); those that still believed the low power approach had more information to yield (eg. Moss 1983, Odell 1985) and later researchers' work that is dissatisfied with the qualitative data provided by Keeley's approach (e.g. Gonzalez-Urquijo and Ibanez-Estevez 2003, Macdonald, 2014). Therefore, it appears that the while the high-powered method characterises much of the sub-field 35 years on, new technologies and methods as well as the lower-power approach are present across the network.

In absolute terms, the network is characterised by mostly neutral and supportive papers in relation to both the determination of implement function (90%) and the type of worked material (93%). However, the centrality analyses reveal that the small number of papers unsupportive of both aspects is cited significantly more often than neutral or supportive papers. These unsupportive articles provide more important links between sections of the network and display significantly higher betweenness centrality (Fig. 3). For the determination of implement function unsupportive papers were significantly closer to the centre of the network than neutral or unsupportive articles. Conversely support for the determination of worked material types was only significantly different in closeness centrality between unsupportive and supportive papers, indicating a more gradual trend to be supportive of this tenet of Keeley's (1980) work, toward the periphery of the network (Figs. 3 & 4). In sum, these results are likely driven by the fact that eight of the ten most cited papers were unsupportive of Keeley's (1980) claim that type of worked material can be discerned form microwear via his methodology, including the most cited paper of the network with an indegree of 53 (Newcomer et al., 1986).

It could be argued, that perhaps these significant differences regarding the unsupportive groups were simply the result of a relatively small sample size with no tail of lower centrality papers. In statistical terms this would hold if samples were drawn from a larger population of papers and unsupportive papers were under-sampled, however, the present data are the full enumeration of the population as per the network definition. Further, a smaller number of nodes would, with all other things being equal, reduce the chances of being cited purely because there are fewer papers to cite. This is borne out in the high-powered microscopy support results which show that the same network produces almost no significant differences and more supportive citations when a different aspect of Keeley's (1980) model is considered (Fig. 3).

The two top clusters in the network, together responsible for ~57% of citations, reflect these centrality trends. While theses clusters are generally supportive (46%) of the high-powered microscopy aspect of Keeley's (1980) approach, this trend is negated for the determination of implement use (50% neutral, 39% unsupportive) and reversed for determination of worked material. The majority of these top two cluster papers are unsupportive of this aspect (54%) and only two articles (Moss, 1987, Bamforth, 1988) are in support of it (Fig. 8).

While most papers are supportive of high-powered microscopy and this method continues to be widely-used, it appears that unsupportive papers regarding function and worked material characterise the centre of this citation network contra our prediction. The formative ideas of Keeley (1980) regarding determination of implement function and type of worked material via his microwear method therefore, seem to no longer characterise the centre of the lithic microwear sub-field, but rather, its periphery.

Type

The distribution of paper types in the network also indicated structure within the network. The most numerous types of paper in the network were AA and papers with a focus other than microwear research or application. The former is, perhaps, expected given that application of microwear analysis should make up the majority of the field. The latter, however, requires some explanation. It is tempting to ascribe the large amount of OF papers to a loose definition of the field yet all employed microwear in some way and referenced Keeley (1980). The relative abundance of OF papers may best be explained by the fact that microwear analysis is a small and relatively recent sub-field of archaeology, and as such, its techniques are employed as an additional rather than a principle methodology in many archaeological studies.

There are relatively few EMR papers and even fewer R papers in the network; although the latter is expected since they can only be written subsequent to other articles. Nevertheless EMR and R articles maintain significantly higher centrality values than the AA and OF papers, with the exception of EMR and AA closeness centrality, which was not significantly larger for EMR (Fig. 6). Though the EMR and R were not significantly different it is interesting to note that EMR papers were cited the most, and that the closeness centralities of the two papers types were similar. This is borne out in the cluster analysis where the two major sub-clusters identified by the algorithm were almost completely EMR and R papers (Fig. 7). The largest difference between EMR and R articles actually occurs in median betweenness centrality where R papers were more often a 'bridge' connecting many papers in the network. This accords well with the prediction that authors would tend to frequently cite review papers focused on the theoretical grounding of their present research.

Perhaps unsurprisingly the paper type analyses demonstrate that the core of the microwear sub-field is experimental microwear research as well as review papers. The EMR articles tend to refine or test methodologies in the sub-field and therefore are cited when these are applied, while R articles draw together the common or accepted knowledge of the sub-field at the time of publication. There is, however, a clear separation between this core of the field and the application of this knowledge in the assemblage analyses. Indeed, 28 of the 64 unconnected papers that only reference Keeley (1980) are assemblage analyses (Fig. 5). This can be explained by the use of Keeley's (Ibid), or a similar qualitative methodology, in these artefactual applications of microwear research, rather than the quantitative experimental microwear methodologies that have since been published and form the centre of the research network, especially those in Cluster 2 (e.g. Stemp and Stemp, 2001, Evans and Donahue, 2008). It could be argued that applications of microwear should be less central since they are employing a method to conduct an archaeological site analysis rather than attempting to refine methodology. Still, the lack of a dialogue between these article types (EMR and AA) implies that any methodological improvements or equivocations are not employed in artefactual applications and conversely, new methodologies are not frequently tested in the complex field environment.

Implications

The present meta-analysis demonstrates that while Keeley's (1980) high magnification light microscopy method is widely supported in the sub-field, this level of support is relatively unstructured in the network and is also enjoyed by other methodologies. Though it should be noted that some modern approaches scored as unsupportive of Keeley's (Ibid.) microscopy method do hold to the ethos of his approach but feel it needs refining (e.g. Stemp et al. 2015b). The results also show that the core of the citation network comprising the sub-field of lithic microwear research is characterised by experimental research and review papers that are generally, though not exclusively, neutral or unsupportive of Keeley's (1980) original tenets regarding implement use and type of worked material. Conversely, the first layer surrounding the core is characterised by lithic artefact assemblage analyses that are largely supportive of these two aspects of Keeley's (1980) model. The periphery of the network is largely neutral articles with another focus. Indeed a test of these associations yields significant associations between these types as reported in Table 3.

Adjusted residuals for Support for the use of high-power microscopy methods (X^2 = 186.14, p =<0.001, V=0.5064)			
	Unsupportive	Neutral	Supportive
AA	0.5248	**-10.932***	**10.776**
EMR	2.4692	**-3.3238***	1.9493
OF	-2.0261	**12.352**	**-11.353***
R	-0.6750	1.6389	-1.2729

Adjusted residuals for Support for the function of tools can be visually identified from microwear (X^2 = 107.78,p =<0.001, V=0.3853)			
	Unsupportive	Neutral	Supportive
AA	-2.0757	**-7.5824***	**8.5502**
EMR	**5.8602**	-0.3597	-2.5556
OF	-2.162	**7.2615**	**-6.1259***
R	-0.3514	0.8432	-0.6615

Adjusted residuals for Support for the type of worked material can be visually identified from microwear (X^2 = 177.24, p =<0.001, V=0.4941)			
	Unsupportive	Neutral	Supportive
AA	-2.7864	**-8.5401***	**10.25**
EMR	**8.3889**	-0.8312	**-4.3326***
OF	**-3.7919***	**9.0239**	**-6.6848***
R	0.5887	-0.1682	-0.1943

Table 3: Adjusted residuals of the chi-Square tests for association between type of paper and type of support. Subsequent to a Bonferroni correction results significant at $p < 0.05$ or critical value ±3 are marked in bold (following Sharpe 2015). *Indicates a significant negative result.

It may be reasonably inferred that the sub-field of microwear, as defined here, has moved away from Keeley's (1980) original conception of the discipline. This shift reflects the adoption of the processual paradigm in the field, as a whole, and increasingly utilised complex metrological and tribological technologies, not available to Keeley in 1980. Experimental microwear research papers may be unsupportive of Keeley (1980) as they have continued to develop or refine his and Semenov's (1957) initial insights. This article makes no-comment on either the efficacy of microwear analysis or the various methodologies it employs. Neither do we mean to imply that Keeley's (1980) qualitative approach is not effective. Yet it is clear that the methodological core of this field has developed into a distinct 'school of thought' from that originally proposed by Keeley (1980). As Van Gijn (2014:168) has expressed: "[t]he method itself has gone through a similar historical trajectory as other new disciplines: from a period of high, unrealistic expectations (1975-1985), through a tumultuous period of rejection and pessimism when the limitations became clear (1985-1990), to the gradual acceptance of the inferential limits, the development of new techniques and the accumulation of empirical evidence". Still, the qualitative method continues to be employed during the analysis of artefact assemblages and there is significant support for Keeley's (1980) optimistic assertion that both implement use and type of worked material can be determined via his experimental microwear program (e.g. Lynch and Hermo, 2015). From the analysis presented here it appears that microwear research has developed into two distinct 'schools of thought' characterised by methodologically focussed quantitative studies and more qualitative artefact studies interpreting material in the field. This analysis, therefore, objectively underlines the calls for standardisation within the sub-field (Evans et al., 2014; Van Gijn, 2014) and the need for these distinct 'schools of thought' to reintegrate to produce a more cohesive microwear discipline.

5. CONCLUSION

The present study generated a citation network to objectively analyse the development of microwear research subsequent to its introduction into the wider academic community by Keeley (1980), concurrent with the development of the processual paradigm in archaeology. Various measures of the importance were generated by centrality algorithms for each of the 363 papers that formed the network while a clustering algorithm delineated the distinct sub-clusters that were at its core. Results demonstrated that the principle two clusters at the centre of the network were chiefly comprised of a small number of experimental microwear research and review papers that were mainly unsupportive of Keeley's (1980) assertions that his model of microwear analysis could determine an implement's function and the type of material worked. These papers were responsible for the majority of citations within the network. Conversely assemblage analyses, which were generally supportive of these aspects of Keeley's model (Ibid), and papers with another focus that were neutral towards the model, formed the less cited periphery of the network. These two objectively identified 'schools of thought' broadly reflect more quantitative and recent articles, as opposed to more widely applied qualitative methodologies akin to Keeley's model. For the first time, this distinction adds objective and statistical weight to recent calls for standardisation within microwear analysis so it may continue to be a growing, cohesive sub-field.

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