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7 **A Citation Network Analysis of Lithic Microwear Research**

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28 **ABSTRACT**

29 The introduction of lithic microwear research into the wider archaeological community by Keeley
30 (1980) was concurrent with the development of the processual paradigm and the adoption of the
31 scientific method. Subsequently, lithic microwear research has benefited from over 35 years of
32 innovation, including the introduction of novel methodological and analytical procedures. The present
33 study employs a citation network to objectively analyse the development of microwear research. Given
34 developments in technology, as well as the institutional isolation of early microwear research, the
35 present analysis considers the citation network that stems from Keeley's seminal 1980 volume . The
36 363 papers identified as having cited Keeley (1980) in the subsequent 35 years were treated as
37 individual nodes within the citation network. Before analysis, nodes were assigned attributes, including
38 the type of research published and whether they were supportive of three key aspects of Keeley's
39 experimental program: the ability to determine the function of the tool and to ascertain the type of
40 worked material from microwear, as well as the use of high-powered microscopy techniques. Emergent
41 properties of the papers, including closeness centrality, indegree and betweenness centrality, are used
42 to test for significant differences between paper attributes. Similarly a clustering algorithm is used to
43 objectively define distinct clusters of important papers within the discipline. Results indicate that a
44 small number of nodes in the network maintain statistically significant influence on the form of the
45 citation network. These important nodes and the distinct 'schools of thought' identified are discussed
46 in the context of Keeley's initial contribution to the sub-field.

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

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78 **1. Introduction**

79 The advent of processual archaeology in the 1960's (Binford and Binford, 1968; Clarke, 1973) marked
80 the adoption of progressively scientific methods within archaeological research. The timing of this shift
81 to include more quantitative methods closely aligns with the development of lithic microwear analysis
82 as a sub-field of archaeological research. In turn, lithic microwear research offers a rare opportunity to
83 examine how a sub-field's accepted knowledge developed in context of the wider adoption of the
84 scientific method. Although many of the key ideas of lithic microwear research were originally
85 conceived of by Semenov (1957) in the 1950's, its introduction into the wider academic community
86 would not occur until the 1960's (Semenov, 1964), developing through the 1970's (Tringham, 1974;
87 Keeley, 1974; Odell, 1975; Hayden, 1979) and resulting in its establishment as a paradigm (*sensu* Kuhn,
88 1962) in the 1980's subsequent to Keeley's seminal volume (Keeley, 1980). An excellent review of this
89 development was conducted by Stemp et al. (2015) who note that Keeley (1980) was motivated to
90 publish, at least in part, by what he viewed as the limited applications of Semenov's original methods
91 in the 1970's. Further, immediately subsequent to this period the introduction of high-powered
92 microscopy marked the beginning of a trend of increasingly sophisticated metrological and tribological
93 instruments utilised by the sub-field (Stemp et al., 2015). Perhaps as a result of the proliferation of these
94 technologies, as well as the continued use of expert qualitative analysis, many methodologies currently
95 exist within microwear studies and there have been calls for standardisation (Evans et al., 2014; Van
96 Gijn, 2014). Yet, in some form, microwear analysis is replete in the literature as it is often included in
97 site reports and therefore can be considered a substantive sub-field.

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

111 We consider the distribution of papers that find evidence for and against three central tenets of Keeley's
112 (1980) experimental microwear program; "...that with the use of high magnification...one can almost
113 always isolate the used portion of the tool and reconstruct its movement during use, as well as, in the
114 majority of cases, determine exactly which material was being worked" (Ibid.:78). Specifically we
115 assess support for: the use of high-powered microscopy methods within microwear research, and the
116 use of this method to determine both tool function and the type of worked material. Since worked
117 material and implement function determination are based on identifying the used portion of a tool, as
118 described by Keeley above, we do not focus on this latter aspect of his work. The present analysis makes
119 no comment on the efficacy or suitability of microwear analysis or its methodologies but instead asks
120 to what extent the sub-field is still characterised by Keeley's (1980) formative ideas. The network is
121 predicted to be mostly supportive of these ideas since they initially defined the sub-field. Similarly,
122 types of paper and their position in the network are also analysed to identify the most influential types
123 of papers in the sub-field. Review papers are predicted to be the most influential type of paper since

124 they draw together the current state of the field at the time of publishing and are often referenced as
125 primer for the reader of original research articles. Finally, emergent properties of the network and sub-
126 clusters within it are analysed in an effort to identify distinct ‘schools of thought’ within the discipline.

127 **2. METHODS**

128 2.1 Node Selection

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

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

142 To sample the relevant literature other citation network studies have used indexed databases of research
143 articles, such as Scopus or PubMed. In the case of archaeology, which has many out-of-publication
144 titles, these databases may not cover the same amount of literature as Google Scholar (Google Inc.,
145 2015), and so this non-indexed database was used. Book chapters are omitted from the present analysis
146 as they are not always available online and so were not compatible with the data collection method used
147 here. Further the availability of printed resources and the potential lack of a peer review process for
148 book chapters may introduce additional variation to the citation network from this distinct publishing
149 process. It would be of interest to extend this analysis to book chapters and non-English language
150 research in the future, but it is beyond the scope of this paper. It could be argued that, as the network is
151 a snapshot of the sub-field in 2015, any papers with a high number of citations are simply the
152 beneficiaries of time. Certainly, the longer something has been part of the literature, the greater the
153 likelihood it has been cited. This would, however, be the case at any cut-off period and controlling for
154 the effects of time by weighting citations may artificially distort the structure of the network in
155 unforeseeable ways. Nevertheless, this potential effect of published year is noted in the discussion.

156 The 363 validated papers were then treated as nodes in the network and each was assigned several
157 attributes separately by authors AK and CD. In rare cases of discrepancy each was re-evaluated.
158 Papers were first categorised as independently supportive, neutral or unsupportive of three key aspects
159 Keeley’s (1980) model: the ability to determine the function of the tool and determine the type of
160 worked material from microwear traces, as well as the use of high-powered microscopy methods.
161 Direct quotes reflecting these respective views from each paper are given in Supplementary
162 Information 1. The criteria used to assign a support categorisation for each variable are given in Table
163 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.

164 **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).

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

166 2.2 Network Creation

167 In order to build the network connections between nodes each citation was treated as a directed edge.
168 The edges were directed since papers could not cite future literature and therefore information could
169 only pass through the network in a directed manner. In order to compute all the edges in the network
170 the reference or bibliography section from papers was either gathered manually as an unformatted text
171 file or, where possible, as a standardised .ris file. Due to natural language inconsistencies across
172 reference lists in papers (such as abbreviations or the inclusion of special characters), a natural language
173 processing algorithm written in Python 2.7.13 (van Rossum and Drake, 1995) by BP was used to extract
174 occurrences of paper titles in these reference lists. From this newly structured data, a graph could be

175 generated by assigning directed edges from title papers (sources) to cited papers (targets). In order to
 176 control for Type 1 errors, matching titles were evaluated for percentage character similarity and any
 177 above 80% were manually verified as either a correct citation or a similar but different paper. This was
 178 important for papers that discussed sites with special characters in their name that could be transliterated
 179 differently depending on the formatting. Further some important papers in the field contain ‘nested
 180 titles’ that contain the full title of another paper preceded by something akin to “a reply to” or suffixed
 181 by “in context”. Since these titles were longer, the exact character match only represented a percentage
 182 of the full title and manual verification was able to eliminate incorrect citations of similarly worded
 183 paper titles. Finally where papers appeared to reference each other reflexively this was manually
 184 verified (see results). This process generated a network containing 1132 citations.

185 2.3 Network Visualisation and Analysis

186 The network was visualised in Cytoscape 3.4.0 (Shannon et al., 2003), an open source software with a
 187 library of plug-ins capable of performing network analysis. Global and nodal network statistics are used
 188 to describe the network and were generated using the Networkx module for Python (Hagberg et al.,
 189 2008).

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

$$193 \quad C_i(x) = \frac{i}{n - 1}$$

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

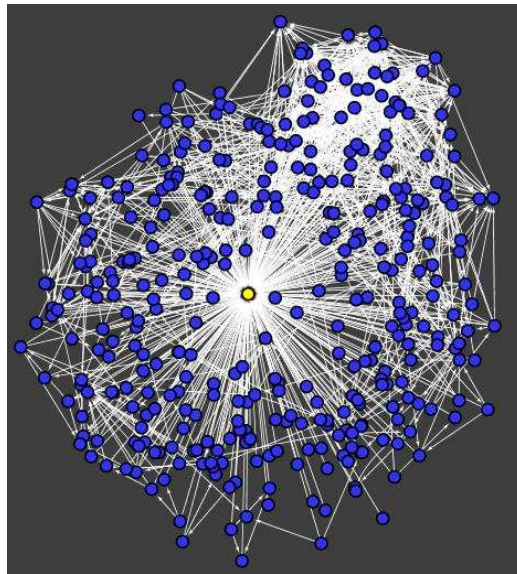
$$203 \quad C_c(x) = \frac{n - 1}{\sum_{b=1}^{n-1} d(x, y)}$$

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

$$211 \quad C_b(x) = \frac{\sum_{y \neq x \neq z} \left(\frac{(y, z) | x}{(y, z)} \right)}{\frac{1}{(n - 1)(n - 2)}}$$

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

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

226 3. RESULTS

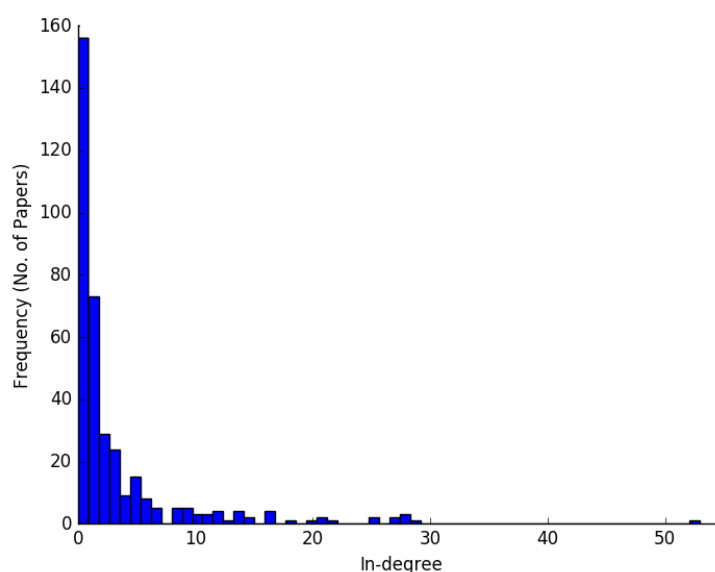
227 The network (Fig. 1) generated from the 363 validated papers is relatively small as the maximum
228 distance from one paper to another is 10 citations (network diameter), yet it is also quite diffuse with a
229 skewed distribution of indegree; some papers are heavily cited whilst many more are not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

236 Of the 363 papers in the network only 9% were classified as unsupportive of the high-powered approach
237 advocated by Keeley (1980) while 42% were neutral on the subject and 49% were supportive. Half of
238 the papers in the network were supportive of Keeley’s (1980) position that the function of an implement
239 could be discerned from microwear, while 43% were neutral and just 7% were unsupportive. Similarly
240 45% of the articles analysed were supportive of the idea that worked material could be discerned via
241 Keeley’s (Ibid.) experimental program, while 44% were neutral and 10% were unsupportive.

242 Due to the disparity of these sample sizes as well as significant deviations from normality, as tested via
243 significant Shapiro-Wilk results, Kruskal-Wallis and Mann-Whitney U pairwise post-hoc tests were
244 used to test for significant differences in network statistics between these groups. A Kruskal-Wallis of
245 indegree between the categories of support for the high powered approach was significant ($H = 6.289$,
246 $p = 0.0489$) and post-hoc pairwise tests show this was the result of supportive papers being cited
247 significantly, but only slightly, more often than neutral ones ($p = 0.0370$). A Kruskal-Wallis of closeness
248 centrality was significant ($H = 6.637$, $p = 0.0362$) but after applying a Bonferroni correction there were
249 no significant differences in network position between papers that differed in their support for the high-
250 powered method. The same omnibus test revealed no significant differences in betweenness centrality
251 between these support groups.

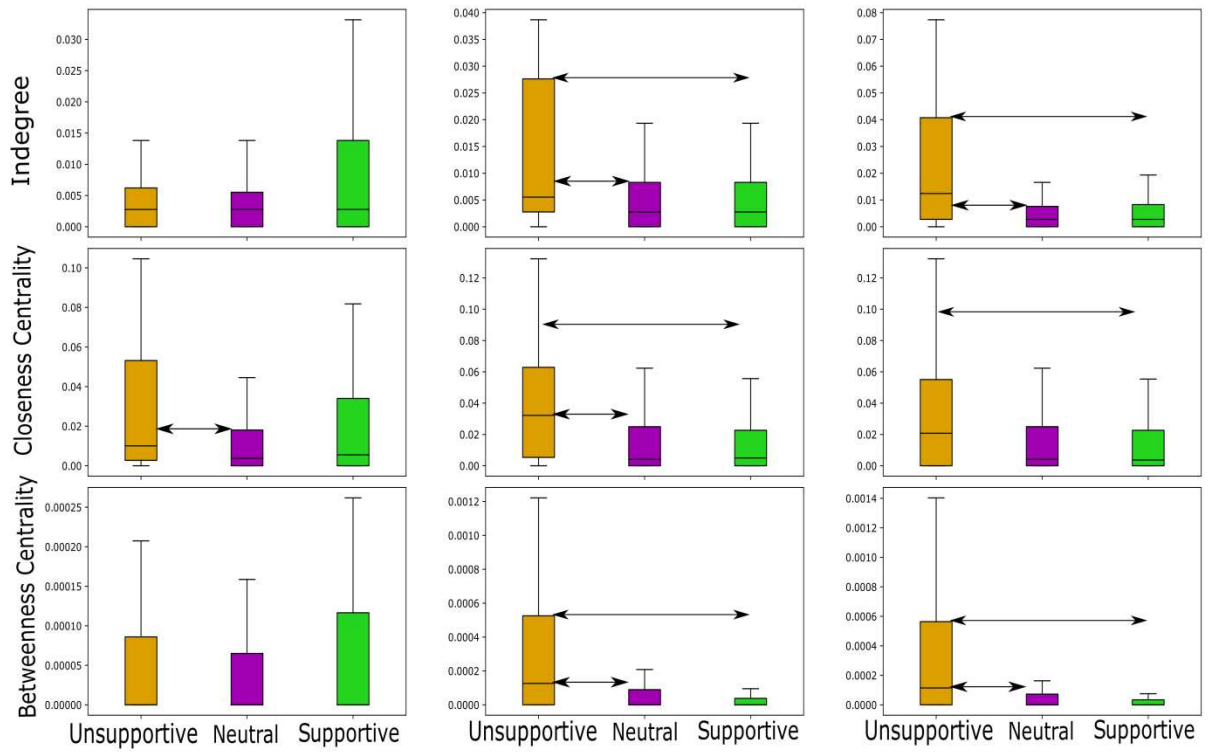
252 Conversely, article support for the determination of implement function via Keeley's (1980) microwear
253 methodology did demonstrate significant differences in network statistics. Kruskal-Wallis tests of
254 indegree ($H = 8.93$, $p = 0.0115$), closeness ($H = 11.28$, $p = 0.0035$) and betweenness centrality ($H = 14.65$,
255 $p = 0.0007$) were all significant and driven by significantly higher values for unsupportive articles than
256 either neutral or supportive papers. Therefore it appears that, despite being a small part of the network,
257 unsupportive papers are cited significantly more, are closer to the centre of the network and are more
258 important in bridging the flow of information than either neutral or supportive papers (Fig 3).

259 Average indegree was significantly different when papers were grouped by their support for Keeley's
260 (1980) claim that worked material can be discerned from microwear ($H = 20.01$, $p < 0.001$) as
261 unsupportive papers were cited significantly more often than neutral or supportive papers. Closeness
262 centrality showed a similar but more graduated pattern with significant differences ($H = 6.487$,
263 $p = 0.0390$) being driven solely by the fact that unsupportive papers were significantly more central in
264 the network than supportive papers, while neutral papers had an intermediate value not significantly
265 different from either other category. Betweenness centrality showed further significant contrasts ($H =$
266 14.65 , $p < 0.001$) due to significantly more important edges in the network passing through
267 unsupportive papers as opposed to neutral or supportive papers with regard to the determination of
268 worked material (Fig.3).



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

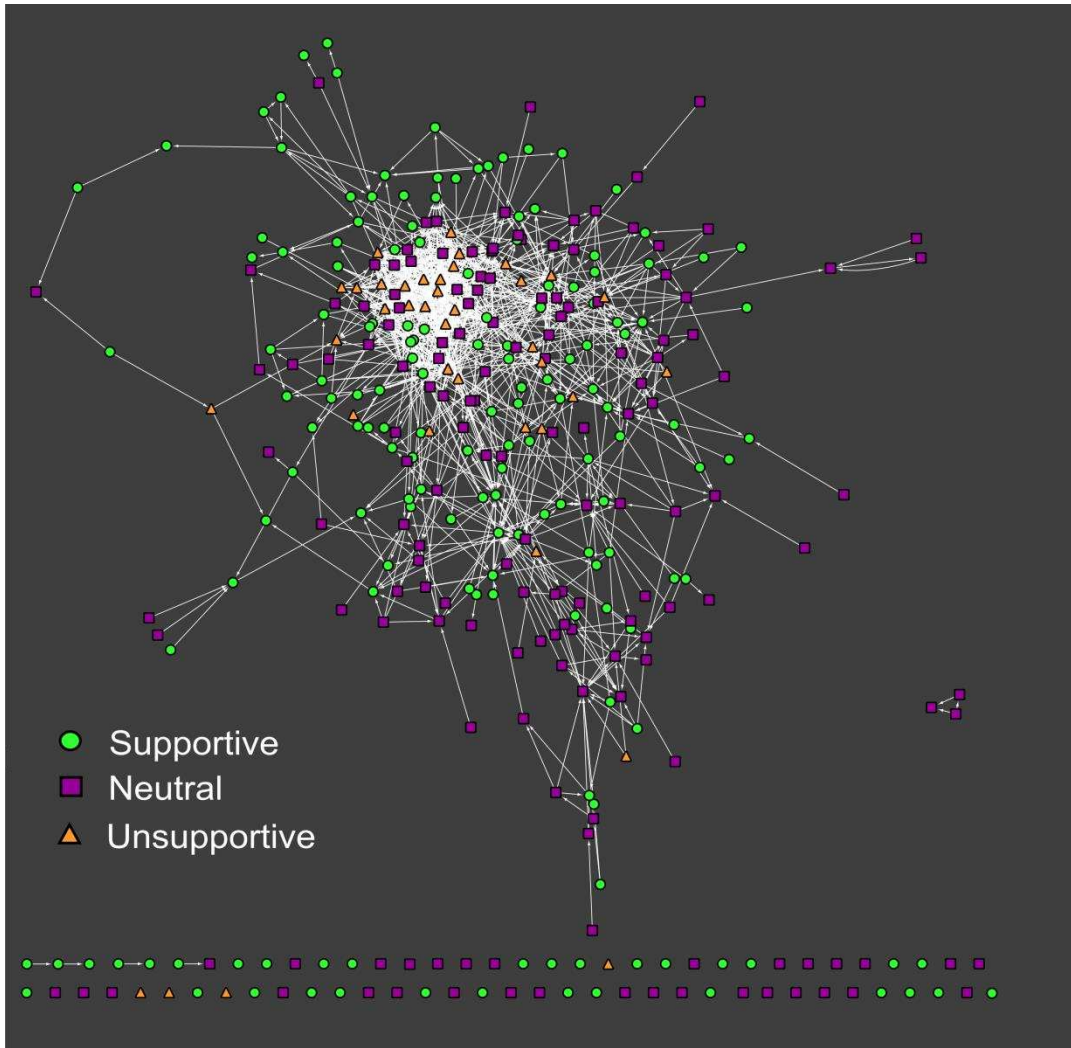


271 Support for High-Powered Microscopy Support for Implement Function Support for Worked Material

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

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

282 3.1 Type

283 As can be seen in Figure 5, AA and OF papers comprise the 36% and 42% of the nodes in the graph,
 284 respectively, with Experimental Microwear Research (EMR) and R papers representing just 16% and
 285 6%, each. Indegree comparisons demonstrated significant differences between the types of paper ($H =$
 286 $87.22, p < .0001$). Specifically, the small number EMR and R papers showed a significantly higher
 287 number of citations than AA or OF papers, and while EMR did receive more citations this was not
 288 statistically distinguishable from R papers (Fig. 6). Closeness centrality also demonstrated significant
 289 differences ($H = 25.72, p < .0001$) between the types of paper with a clear separation of AA and OF
 290 papers from the EMR and R papers. However, here EMR papers closeness centrality was not
 291 significantly higher than AA, while R papers were slightly more central than EMR papers (Fig. 6). As
 292 hypothesised, betweenness centrality values were significantly higher for the R papers than other types
 293 ($H = 42.28, p < .0001$) though it was not significantly larger than EMR papers after the Bonferroni
 294 correction.

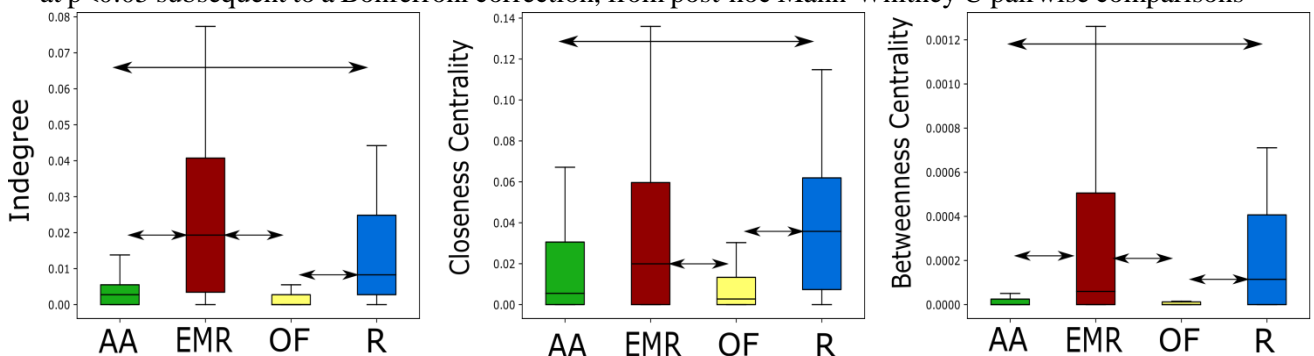
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298 **Figure 5:** The network of 363 validated research papers with each node coloured by the type. Nodes
 299 placed at the bottom of the figure represent papers that only cited Keeley (1980) and were not cited by
 300 other articles within the network.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

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



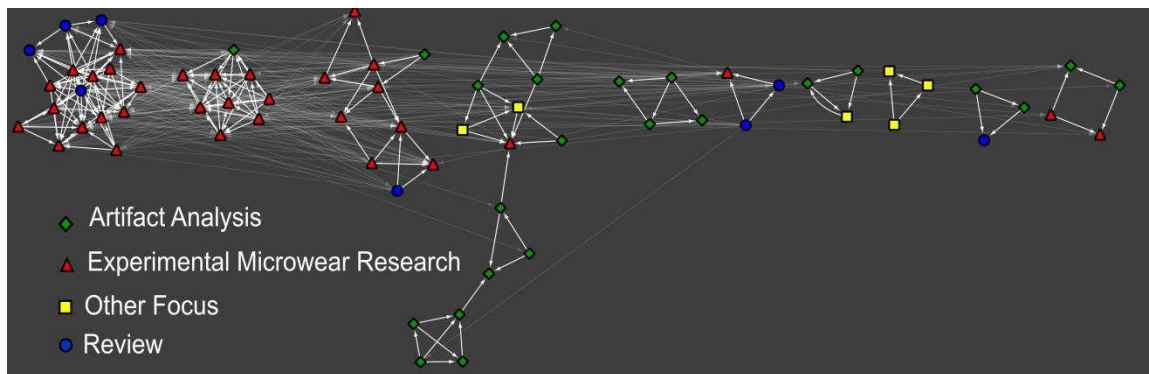
303 are indicated by black arrows.

304 3.2 Cluster Analysis

305 Using standard parameters the MCODE algorithm was able to identify 10 unique sub-clusters within
306 the network as visualised in Figures 7 and 8. The 71 nodes within these clusters represent ~20% of the
307 total network and represent ~71% of the total citations in the entire network. The first two clusters
308 represent the ‘core’ of the network with MCODE scores of 8.125 and 8, respectively, whereas clusters
309 3-10 have scores from 3.556 – 2.667. Clusters 5-10 represent specific concentrations; Cluster 10
310 comprises papers concerned with residue analysis and hafting (e.g.Dinnis et al., 2009), Cluster 9
311 represents several analyses by E.H. Moss (1983, 1986, 1987), Cluster 8 concerns ethnoarchaeology
312 (Atherton, 1983; Agorsah, 1990; Cunningham, 2003), Cluster 7 represents papers concerning Paleo-
313 Indian of North America by D.B. Bamforth (1985, 1986, 1991), Cluster 6 comprises 21st century papers
314 on blind-testing as a methodology (Rots et al., 2006; Evans, 2014; Evans et al., 2014) and Cluster 5
315 mainly concerns Paleo-Indian bladelets (Yerkes, 1994; Kay and Mainfort, 2014; Miller, 2014, 2015).
316 Cluster 4, containing 15 nodes, is dominated by assemblage analyses from the Levant, Africa and
317 Europe but is also rooted in two papers that consider the effect of post-depositional and environmental
318 factors on surface microwear (Sala, 1986; Burrioni et al., 2002). Cluster 3 contains 16 nodes mostly
319 focussed on quantifying microwear with microscopy and other processes that impact on the formation
320 of microwear (Grace et al., 1985; Stemp et al., 2012; Lerner, 2014; Olle and Verges, 2014).

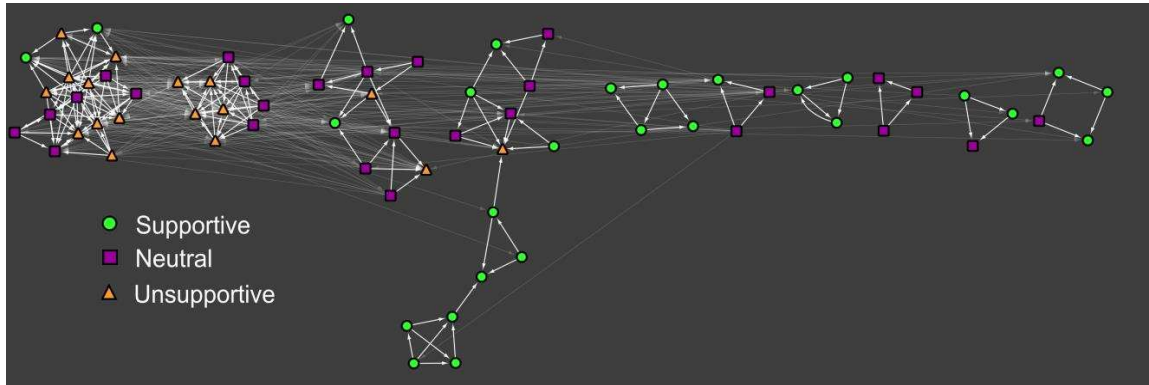
321 Cluster 2 only contains 9 nodes but comprises 23% of the citations in the network. This cluster is almost
322 entirely EMR papers concerning metrology, quantification and the development of microwear using
323 new microscopic methods (Stemp and Stemp, 2001, 2003; Evans and Macdonald, 2011; Borel et al.,
324 2014; Key et al., 2015), although it also includes one of the oldest interferometry papers in the field
325 (Dumont, 1982). Indeed, even the single AA paper in Cluster 2 employs atomic microscopy (Faulks et
326 al., 2011). Cluster 1 is the core of the graph with 17 nodes and integral to 34% of the citations in the
327 network. The papers in this cluster are all EMR and R papers, including those concerning the original
328 debate over blind testing methodology from the 1980’s (Newcomer et al., 1986, 1988; Moss, 1987;
329 Bamforth, 1988), as well as quantitative analyses and methodological testing papers (Stemp et al., 2008,
330 2009, 2010 ,2014; Evans and Donahue, 2005; Evans et al., 2014). Both Clusters 1 and 2 have articles
331 mostly unsupportive (56%) of Keeley’s (1980) assertion that worked material can be identified from
332 microwear in contrast to all of the other identified clusters (Fig.8). For the determination of implement
333 function Cluster 2 has one more neutral than for worked material but is otherwise the same. Conversely,
334 Cluster 1 is predominantly neutral for implement function with less unsupportive papers (30%) and one
335 further supportive article than the two for worked material.

336



337

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



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

346 4. DISCUSSION

347 The Network

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

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

360 Support

361 High-powered microscopy is central to Keeley's (1980) program and is perhaps one of the clearest
 362 aspects in which his work departs from earlier studies such as Semenov (1964). In terms of number of
 363 papers, the network was 49% neutral and 42% supportive of this aspect of Keeley's work. While not
 364 statistically significant, supportive papers, that largely employed the technique for assemblage analysis,
 365 were cited more often in the network than neutral or unsupportive articles (Fig.3). The only significant
 366 difference regarding high-powered microscopy was that unsupportive papers were closer to the centre
 367 of network than neutral papers, though not more so than supportive ones. Unsupportive papers
 368 constituted older papers that applied a low-power approach (e.g. Stafford and Stafford, 1983, Kenmotsu,
 369 1990); those that still believed the low power approach had more information to yield (eg. Moss 1983,

370 Odell 1985) and later researchers' work that is dissatisfied with the qualitative data provided by
371 Keeley's approach (e.g. Gonzalez-Urquijo and Ibanez-Estevez 2003, Macdonald, 2014). Therefore, it
372 appears that the while the high-powered method characterises much of the sub-field 35 years on, new
373 technologies and methods as well as the lower-power approach are present across the network.

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

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

396 The two top clusters in the network, together responsible for ~57% of citations, reflect these centrality
397 trends. While these clusters are generally supportive (46%) of the high-powered microscopy aspect of
398 Keeley's (1980) approach, this trend is negated for the determination of implement use (50% neutral,
399 39% unsupportive) and reversed for determination of worked material. The majority of these top two
400 cluster papers are unsupportive of this aspect (54%) and only two articles (Moss, 1987, Bamforth, 1988)
401 are in support of it (Fig. 8).

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

407 Type

408 The distribution of paper types in the network also indicated structure within the network. The most
409 numerous types of paper in the network were AA and papers with a focus other than microwear research
410 or application. The former is, perhaps, expected given that application of microwear analysis should
411 make up the majority of the field. The latter, however, requires some explanation. It is tempting to
412 ascribe the large amount of OF papers to a loose definition of the field yet all employed microwear in

413 some way and referenced Keeley (1980). The relative abundance of OF papers may best be explained
414 by the fact that microwear analysis is a small and relatively recent sub-field of archaeology, and as such,
415 its techniques are employed as an additional rather than a principle methodology in many archaeological
416 studies.

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

428 Perhaps unsurprisingly the paper type analyses demonstrate that the core of the microwear sub-field is
429 experimental microwear research as well as review papers. The EMR articles tend to refine or test
430 methodologies in the sub-field and therefore are cited when these are applied, while R articles draw
431 together the common or accepted knowledge of the sub-field at the time of publication. There is,
432 however, a clear separation between this core of the field and the application of this knowledge in the
433 assemblage analyses. Indeed, 28 of the 64 unconnected papers that only reference Keeley (1980) are
434 assemblage analyses (Fig. 5). This can be explained by the use of Keeley's (Ibid), or a similar qualitative
435 methodology, in these artefactual applications of microwear research, rather than the quantitative
436 experimental microwear methodologies that have since been published and form the centre of the
437 research network, especially those in Cluster 2 (e.g. Stemp and Stemp, 2001, Evans and Donahue,
438 2008). It could be argued that applications of microwear should be less central since they are employing
439 a method to conduct an archaeological site analysis rather than attempting to refine methodology. Still,
440 the lack of a dialogue between these article types (EMR and AA) implies that any methodological
441 improvements or equivocations are not employed in artefactual applications and conversely, new
442 methodologies are not frequently tested in the complex field environment.

443

444 Implications

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

457

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

458

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

459

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

460

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

464 It may be reasonably inferred that the sub-field of microwear, as defined here, has moved away from
 465 Keeley’s (1980) original conception of the discipline. This shift reflects the adoption of the processual
 466 paradigm in the field, as a whole, and increasingly utilised complex metrological and tribological
 467 technologies, not available to Keeley in 1980. Experimental microwear research papers may be
 468 unsupportive of Keeley (1980) as they have continued to develop or refine his and Semenov’s (1957)
 469 initial insights. This article makes no-comment on either the efficacy of microwear analysis or the
 470 various methodologies it employs. Neither do we mean to imply that Keeley’s (1980) qualitative
 471 approach is not effective. Yet it is clear that the methodological core of this field has developed into a
 472 distinct ‘school of thought’ from that originally proposed by Keeley (1980). As Van Gijn (2014:168)
 473 has expressed: “[t]he method itself has gone through a similar historical trajectory as other new
 474 disciplines: from a period of high, unrealistic expectations (1975-1985), through a tumultuous period
 475 of rejection and pessimism when the limitations became clear (1985-1990), to the gradual acceptance
 476 of the inferential limits, the development of new techniques and the accumulation of empirical
 477 evidence”. Still, the qualitative method continues to be employed during the analysis of artefact
 478 assemblages and there is significant support for Keeley’s (1980) optimistic assertion that both
 479 implement use and type of worked material can be determined via his experimental microwear program

480 (e.g. Lynch and Hermo, 2015). From the analysis presented here it appears that microwear research has
481 developed into two distinct ‘schools of thought’ characterised by methodologically focussed
482 quantitative studies and more qualitative artefact studies interpreting material in the field. This analysis,
483 therefore, objectively underlines the calls for standardisation within the sub-field (Evans et al., 2014;
484 Van Gijn, 2014) and the need for these distinct ‘schools of thought’ to reintegrate to produce a more
485 cohesive microwear discipline.

486 **5. CONCLUSION**

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

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516

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