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Quantifying scientific significance of a fossil site: the Gogo Fossil sites (Late Devonian, Western Australia) as a case study

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Abstract

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Assessing the scientific significance of fossil sites has up to now been largely a matter of subjective opinion with few or no metrics being employed. By applying similar metrics used for assessing academic performance, both qualitative and quantitative, to fossil sites we gain a real indication of their significance that enables direct comparison with other sites both nationally and globally. Indices suggested are those using total pages published for both peer-reviewed and combined peer-reviewed and popular publications, total citations from the papers, total impact points for site (citing palaeontology-related papers only), total number of very high impact papers (VHIP; journal impact factor>30) and social media metrics. These provide a measure of how much the published fossil data from a site has been utilised. The Late Devonian fossils of the Gogo Formation of Western Australia are here used as an example of how these metrics can be applied. The Gogo sites for example, have produced c.4384 pages of peer-reviewed papers (c.5458 total combined with popular works); generated papers with a total impact point score of 611, including 10 VHI papers, and generated 4009 citations. The sites have an overall h-index of 33. Combing these into a Scientific Site Significance Index (SSSI) will permit direct comparisons of site significance to be made for initiating discussions about site protection, tourism, geopark status, local heritage listings or potential future world heritage nominations.

Keywords natural heritage, palaeontology, Paleozoic.

Introduction

Tom Rich once said in an interview with Natalie O'Brien of The Australian, that Gogo was "the most important fossil vertebrate site in Australia" (The Australian, 2nd August, 2001, p.4). Whether or not one agrees with such a statement is completely arbitrary, but such statements raise a number of questions concerning how we routinely assess the scientific significance of a fossil site. Fossil sites are non-renewable resources that may hold values ranging from the tangible, in terms of scientific significance and economic values to local tourism, but they may hold other values in terms of cultural significance when fossil sites coincide with places valued by indigenous peoples, or be historically significant in their own right (e.g., Wellington Caves, New South Wales; Lake Eyre Basin, South Australia; Rich & Archbold, 1991). Fossils can also hold intangible natural heritage values making them far more significant than their net scientific worth as can geological sites (Pena do reis & Henriques, 2009; Long, 2012a). An example of this is the Gogo fish *Mcnamaraspis* (fig. 2A) which in December 1995 became historically significant as the first state fossil emblem to be formally decreed in Australia (Long, 2004; https://www.dpc.wa.gov.au/GuidelinesAndPolicies/SymbolsOfWA/Pages/FossilEmblemGogoFish.aspx).

Although there are several papers evaluating geoheritage sites (e.g. Pena do reis & Henriques, 2009) there are none the author knows of that specifically attempt to evaluate the scientific significance of a fossil site using an applied approach. To initiate discussion on potential methods to evaluate the significance of any fossil site, this paper will analyse the Gogo fossil sites in north Western Australia, of late Devonian age (Frasnian), in terms of various metrics which allow a comparative measure of scientific significance as is generally applied to measuring academic performance. This approach is based on the premise that a site rich in fossils of high diversity and significance will have been targeted for primary research. If the papers are indeed significant they will have been used in other studies and thus be cited frequently. If the work has high international significance then the work will most likely have been published in high impact multidisciplinary science journals, if the discoveries were made in relatively recent times. Many highly significant sites lack extensive publications in these journals as I acknowledge that the need to publish in high impact journals is a relatively recent phenomenon tied to increased grant success and even academic promotion. If the fauna from a site is highly diverse it should also result in large number of publications being developed, and possibly have

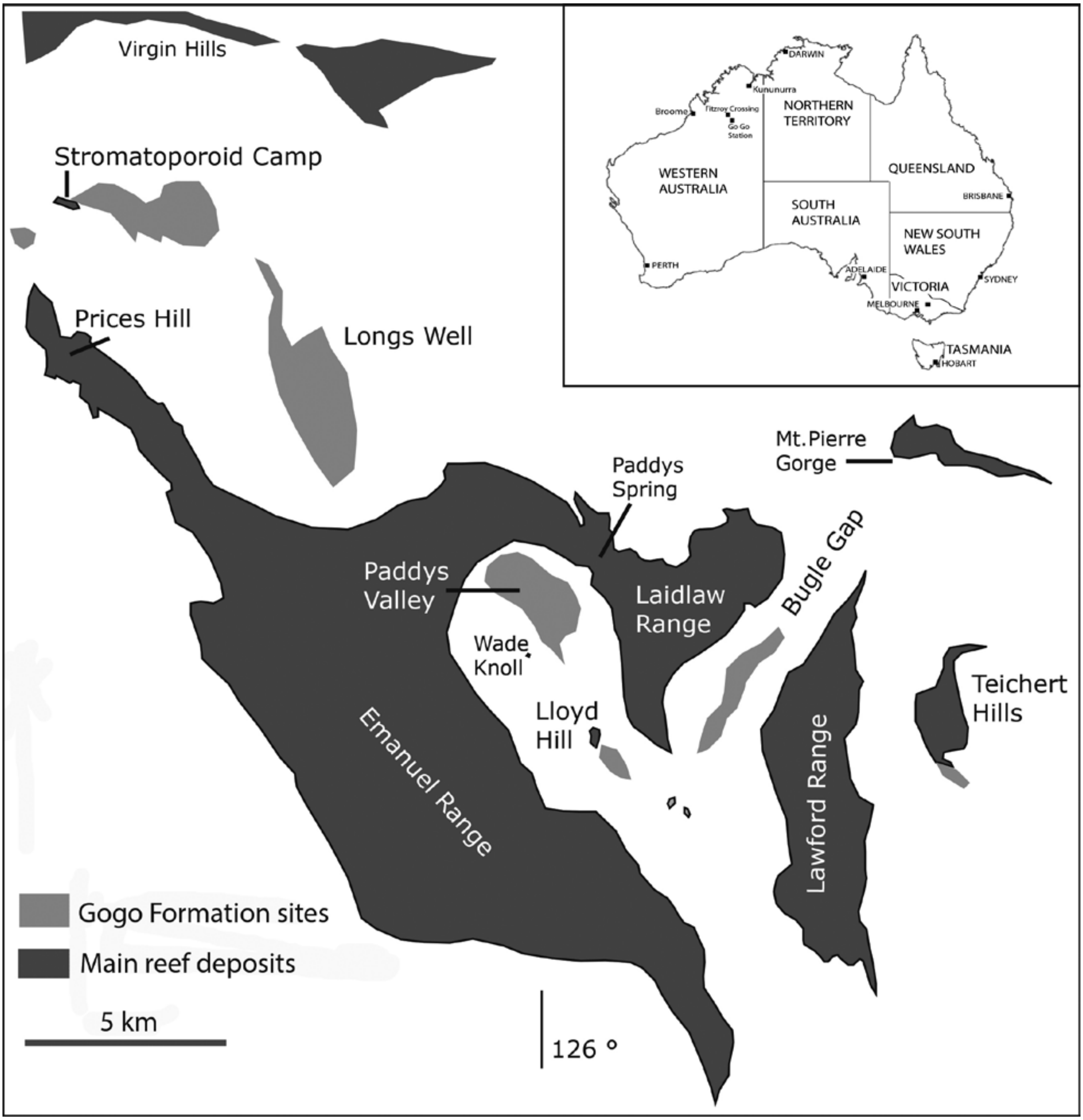

Figure 1. Map showing area covering the Gogo Formation site localities (geology taken from Long and Trinajstic, 2010, figure 1).

produced large numbers of published pages. As scientific papers can range from a one-page abstract to several hundred page monographs, the number of scientific publications on the fossil fauna and/or flora of a site is here considered of far less importance than the total numbers of peer-reviewed pages published. Finally, like routine academic performance, a high citation rate from papers produced around a site can be expressed as an h-index (numbers of publications having equal or greater numbers of citations) for each site. In palaeontology, unlike other mainstream science disciplines, there is a smaller pool of active academics (compare with say medicine or biology in general), so overall citation rates tend to be low.

A fossil site is used here is in the broader context to contain all individual sites from similar formation defined as follows: a set of sites within a contained area that is linked by having fossils of similar preservation coming from the same geological

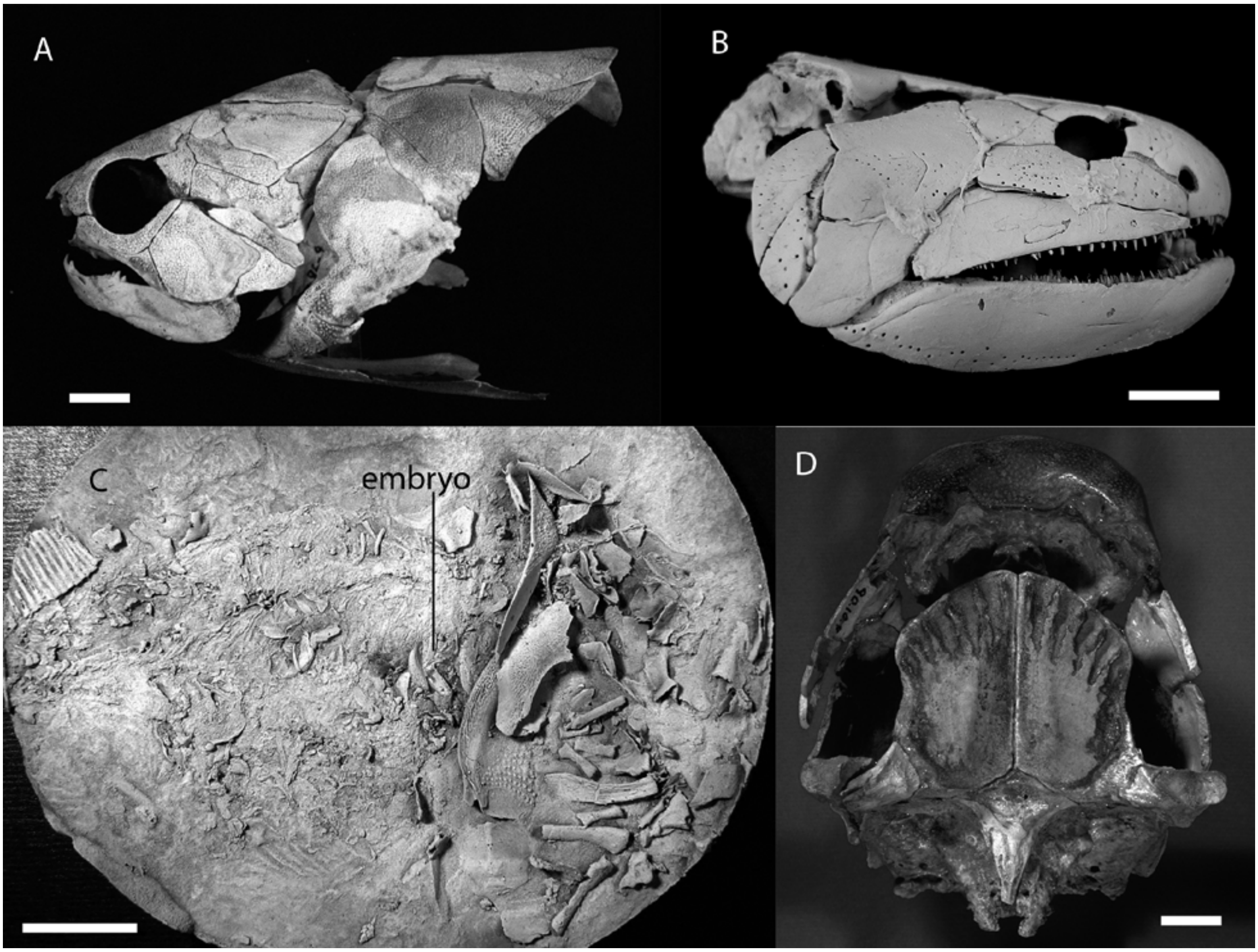

Figure 2. Examples of Gogo fish preservation (WAM = Western Australian Museum; NMV P = Museum Victoria Palaeontology Collection). A, eubrachythoracid placoderm *Mcnamaraspis kaprios*, the state fossil emblem of Western Australia (WAM 86.9.676, from Long, 1995). B, The tetrapodomorph fish *Gogonasus andrewsae* (NMV P221807). C, the ptyctodontid placoderm *Austroptyctodus gardineri* which has 3 embryos preserved inside it (WAM 86.9.662). D, palatal view of the lungfish *'Chirodipterus' australis* (most likely a new genus). WAM 90.10.8. Scale bars are 1 cm.

formation, of approximate same stratigraphic age, and same palaeoenvironment. The Gogo sites comprise a large number of individual sites across an area of about 200km^2, so the term "Gogo fossil sites" refers to a suite of sites containing well-preserved fossils all found from surface limestone concretions derived from exposures of the Gogo Formation (fig. 1). Most of the better known sites are listed by Miles (1971). The sites comprises one of only 6 recognised Lägerstatten (sites of exceptional quality fossil preservation), designated for the known fossil fish sites of this age globally, as listed in the supplementary information (Anderson et al., 2011).

In this paper the measure of that significance is discussed with respect to factors that apply to measuring academic outputs in terms of both quantitative (numbers of significant specimens as a corollary of numbers of significant scientific papers) and qualitative measures (quality of preservation, disparity of species variation also translating into a diversity of scientific papers). The metrics applied are provided in Supplementary Appendix 1. Natural History collections can be evaluated in a similar way, as shown by Winkler and Withrow (2013). By creating a Google Scholar profile for the bird collections at the University of Alaska Fairbanks Museum, they were able to show that the body of work supported by the collection had a profile h-index of 42, equivalent to that of an average Nobel Laureate in Physics. Similarly the Louisiana Museum of Natural History bird collections have their own Google scholar page that now records an h index of 69 (based on 25,469 citation as of December 1st, 2014). These measures thus send a positive message of how significant these collections are by virtue of how well used and cited is the work on its specimens. A similar approach is proposed in this paper to show how well utilised the scientific papers generated from a particular fossil site can be applied to give an indication of the site's scientific significance.

It is important to be able to quantifiably measure the relative significance of a fossil site for varying applications: assessing heritage status for local conservation planning, for issuing permits for collecting for scientific work in national parks (or when sites fall under the auspices of local shire land management); and for potential future nominations for national heritage registers and international recognition including potential future world heritage nominations.

Previously fossil sites have been assessed for the old register of national estate (national heritage listings) based on how expert assessors with specialist knowledge of the site and its fauna position them within an arbitrary framework relative to other known sites. The problem with this is that the individual specialist who knows a particular site well may not necessarily be familiar with the full body of scientific literature on other sites of different age and faunal composition. This informal placement of sites as 'highly significant' or extremely important lacks a quantitative approach that can be used to argue that other sites that are potentially above the average local or national significance, and thus help target future sites in need of some form of legislative protection against site damage by non-professional collectors or fossil dealers (see Long, 2002, for case examples). The Gogo sites have been chosen as the case study in this work mainly because of the author's familiarity with the site, having collected at the localities for the past 30 years and worked on its vertebrate fauna for the past 30 years, and from being familiar with its extensive scientific and popular literature.

The Gogo Fossil Sites and Inferred Scientific Significance

The significance of the Gogo Fossil sites were recognised in the 1960s when the acetic acid preparation technique was refined at the Natural History Museum, London by Harry Toombs (Toombs, 1948). Toombs was able to prepare 3-D skeletons of Devonian fishes out of limestone, revealing perfect 3-D shape and form. Furthermore, in recent years preservation of fossil impressions of soft tissues including muscle fibres (Trinajstic et al., 2007, 2013), nerve cells (Trinasjtic et al., 2007), umbilical structures and embryos (Long et al., 2008, 2009, Trinajstic et al., 2014; also see fig 2C) and alimentary structures (Long and Trinajstic, 2010) have been identified. Examples of the 3-D preservation of Gogo fishes and embryos is shown in figure 2. Biomarkers have recently been identified in Gogo crustaceans preserving proteins only found in living crustaceans (Melendez et al., 2013). The real utilisation of the Gogo fossil fish fauna though is due to the clear unambiguous preservation of the bony skeletons. It has been widely utilised for detailed histological studies of early vertebrate tissues (e.g. Smith, 1977; Smith & Campbell, 1987 etc.), as well as inclusion in major phylogenetic papers analysing character distributions (Miles and Dennis, 1979; Miles and Young, 1977, Long et al., 2014). The landmark paper on transformed cladistics by Rosen et al. (1981) utilised Gogo lungfish material to press home certain points about the homology of the tetrapod choana. Today this paper has been cited nearly 400 times (Google Scholar) and remains a seminal work on the topic.

In terms of non-quantifiable highlights of the Gogo fauna's significance, this includes a series of world first or unique occurrences of species, genera and families. The Gogo fauna contains a mostly endemic fauna of around 90% unique genera and species. It contains the world's only known record of camuropiscid and inscisoscutid arthrodires. It also contains the highest diversity of lungfishes (c. 12 spp.) and actinopterygians (c. 5 spp.) for any site of similar age. In its high diversity of vertebrates (c. 50 spp.) it is well above any other site of similar age, including the World Heritage Miguasha site in Canada (20 fish species; Cloutier, 2010). From a purely intuitional perspective one can sense the value and degree of scientific significance of such a uniquely well-preserved, diverse and endemic fauna is obviously high. The question is how do we measure this?

Gogo Sites: Actual Measures of Scientific Significance

The premise of this work implies that the diversity of a fauna is reflected in the numbers of papers on the fauna, and the numbers of pages of peer-reviewed publications. Works of monographic stature indicate seminal papers that are widely cited as the key reference for the study group (e.g., Gardiner's 1984 monograph on Gogo actinopterygians has 250 citations). Thus sites of high scientific significance would be expected to generate not only a lot of papers, but large descriptive papers and therefore highly cited papers. Large monographic works are amongst some of the most highly cited works in palaeontology, and on-line journals like *Paleontologia Electronica* still publish such works without charge to authors. A good measure for the total significance of a body of work centred around a topic is the cumulative impact factor points of the journals they have been published in. The academic website ResearchGate uses this approach by adding up the impact factor points for an individual's body of work to give a total tally. Using this approach we find that the Gogo sites have an impact factor points tally of around 611. The method used in the scoring was to assign low ranking journals (IF=0-1) as a score of 1, and then round up or down any other impact factors to the nearest whole numbers.

Assessing very significant fossil specimens. A fossil that solves a major evolutionary problem or bridges a major morphological boundary as a key transitional form will attract high numbers of citations. For example the discovery of *Tiktaalik*, which was found to be the immediate ancestor of all living tetrapods, was published in the journal N*ature* as two back-to-back articles in April 2006 (it was also the cover story). To date these two papers on *Tiktaalik*, now one of the most well-known and iconic fossil discoveries of the 20th century, have received 255 citations (Daeschler et al., 2006) and 188 citations (Shubin et al., 2006) respectively. Yet a third paper on *Tiktaalik*, also published in *Nature* (Downes et al., 2008), has only received 25 citations. Another example is the discovery of *Homo floresiensis,* the so-called 'hobbit'. The initial paper announcing the discovery by Brown et al. (2004) in *Nature* has now received around 609 citations. Using these as a reasonable basis for comparison, we see that the Gogo fauna's most highly cited descriptive papers (Miles, 1977, 188 citations; Gardiner, 1984, 250 citations), though not published in high impact journals, still yield high citations directly comparable to the original *Tiktaalik* papers.

Very High Impact Papers. One measure of the international significance of fossil specimens is whether they are valuable in solving a major phylogenetic or biogeographic problem, or provide new information about evolutionary biology deemed highly significant. In such cases the work is occasionally accepted in the highest ranking interdisciplinary science journals like *Nature* or *Science*. Of course, this is not always the case as some very significant discoveries get routinely rejected by such journals. Nonetheless, as these journals publish only a handful of palaeontological papers each year (e.g., *Nature* published about 10 palaeontological papers in 2014), each paper is judged to be a highly significant breakthrough worthy of high impact publication by both the board of editors and reviewers of these papers. These are thus here given special attention as 'very high impact papers' (impact factor as of 2013 > 30; Nature, IF=42; Science IF=31).

A measure of international significance for a site can therefore be also gauged by the total number of very high impact papers (VHIP) published on its fossil materials. For the Gogo sites, this amounts to 10 such papers (9 on primary materials, plus one review paper on the site's significance, Ahlberg, 1989; see Supplementary Appendix 1). This is more VHIPs than any other fossil site in Australia (for comparison, Riversleigh World Heritage fossil mammal site has 4 VHIPs, Victoria's Early Cretaceous vertebrate sites have 4 VHIPs, Ediacara c. 3 VHIPs). Excluding African hominid sites, the only other fossil sites in the world that immediately come to mind to have 10 or more VHIPs published on their faunas would include the Jehol Biota of China (Liaoning sites, covering a very wide range of sites and stratigraphic horizons), and the Burgess Shale sites in Canada.

Numbers of papers/pages published. This gives an overall estimate of the quantity, but not quality, of peer-reviewed work published from a site. Naturally a large number of papers reflect either a diverse fauna, or that continuous new data is being described from a site. This suggests the site hasn't yet peaked in terms of yielding scientifically significant new specimens. In some cases work might be published as a series of monographs, which limits the overall numbers of papers published but increases the total number of pages of published work. For Gogo this is a large number: 4389 pages. This excludes any books that are not specifically on the Gogo fossil fauna. This doesn't include papers on the geology of the site, but only papers that primarily describe Gogo fossils (fishes plus invertebrates and microfossils) or figure Gogo specimens in elucidating the descriptions of other early vertebrate specimens.

Other measures of the cultural and scientific significance of a site

Books and popular magazine articles published. Both technical and popular books centred around the fossil biota of a site can be used to gauge its significance as only books that publishers see worthy of competing in the market will be published by mainstream or academic publishers. In other words a site yielding information that is a consumable product for the general public rather than just for a specific scientific audience will get published by major publishers (excluding self-published projects). In such cases, we can also corroborate publication about the site in a number of popular science magazine publications (e.g., *New Scientist, Scientific American, Discover, Cosmos, Australasian Science* etc.) as well as being subject material for popular books for the adult lay audience. This has been achieved for the Gogo fauna, with many articles appearing in the international popular science journals (eg *New Scientist*, April 1989; *Scientific American,* cover story for January 2011). This includes books written about the evolution of fishes featuring Gogo specimens (Long, 1995, 2011a), as well as a history and significance of the Gogo fossil discoveries (Long, 2006), a book telling the story of the origins of copulation (Long, 2011b, 2012b) and a children' s book about the story of Gogo fish becoming a state fossil emblem (Long, 2004).

Media Focus on the Site. The international significance of a fossil site can also be measured in terms of how much national and international media coverage the site has generated through inclusion in general documentary programs covering broad topics like vertebrate evolution or the prehistory of a country. The Gogo sites featured in David Attenborough's 1979 series *Life on Earth* (episode 4, fishes), and in recent years featured on other local documentaries made about Australia's prehistoric past (e.g., Richard Smith's Australia: Time Traveller series, ABC TV, 2012). Gogo fish fossils have also been the topic of 3 features screened on the ABC TV's science program *Catalyst* (formerly called '*Quantum*'). Social media could be another way to measure impact or visibility of a site, using popular web blog sites like 'The Conversation' to highlight the significance of certain sites. Altmetrics from such sites record numbers of hits, tweets and media pick-ups on each article.

Tourism. The amount of tourism to a site (e.g., annual number of visitors), funds raised by visitations, sales, and so on could also be applied if the site was open to the public (e.g., Naracoorte Caves world heritage site). These metrics really only apply to the sites that can capture such visitations and their associated funding.

A Proposed Site Significance Index (SSSI)

One way of generating a usable index of scientific significance is to arbitrarily combine all the metrics discussed above into a formula that smooths out the very high numbers with the low but significance indices.

Ppr=pages published (peer-reviewed) is a large number for Gogo, so Ppr/100 gives 4389/100 =43.89, rounded up to 44.

Ip=Impact points 611 is also a large number so Ip/10 gives 611/10=61.

Cn=Total citations is also a large number, so Cn/100 gives 4009/100=40 (rounded).

VHIP=very high impact papers is always a relative low number so needs to be multiplied by 10 for a reasonable comparison with other sites where VHIP might regularly be less than 5. For Gogo this gives 10x10=100. This measure is seen to be highly significant as an index of globally significant papers.

The suggested formula for assessing site significance that brings these factors into account would be: SSSI=(Ppr/100)+(Cn/100)+(Ip/10)+(VHIP x10).

For the Gogo sites as assessed at the time of submission of this work, this score is

SSSI=44+40+61+100=245.

The meaning of such a score can only be assessed when further work is completed on other significant fossil sites to measure and compare the same metrics. As this paper was intended primarily to be a generator of discussion, I hope that this will incite other researchers to score other fossil sites they have worked on, particularly those who have focussed on a special fossil site for most of their working careers so that the body of published information on the site is captured. This will enable other fossil sites to be eventually compared with one another using the metric approach here outlined. It is also hoped that further discussion on this topic will be generated by this paper to determine if the parameters chosen herein are suitable enough or if other factors need be scored and added into the mix to give a more meaningful assessment of a fossil site's scientific significance.

Acknowledgements

This paper is dedicated to Dr Thomas H. Rich who has been one of the most inspirational mentors towards my early career development. Tom dedicated many years of his life working the Victorian Cretaceous fossil sites in search of our country's oldest mammals, and he eventually found them after many years of hard searching. He has taught me and many of my colleagues the value of persistence in working a site year after year until the very significant fossils are eventually found. The MS has benefitted from discussions with Erich Fitzgerald, Gavin Prideaux, Gavin Young and Kate Trinajstic.

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Supplementary Appendix 1.

Gogo Fossil publications (palaeontology only, papers primarily concerned with palaeontology or fossil preservation/ diagenesis, not primarily geology or background information). Includes page numbers, impact factors, and citations. Impact factors (IF) based on 2013 scores rounded up or down to nearest full number (eg 2.34=2, 2.56 =3), journals with no recorded impact factor or those lower than 1 are here allocated an arbitrary score of '1'; citations from google scholar (cn, as of Nov 20-21, 2014). Incudes primary references on Gogo fossils, major review papers on Gogo fossils, plus peer-reviewed papers illustrating Gogo specimens to assist with morphological interpretation of other materials. Only publications which have citation and or impact factor metrics are recorded.

VERY HIGH IMPACT PAPERS (IF>30)
(full references cited below).

1. Rolfe1966 (Nature)
2. Ahlberg 1989 (Nature)
3. Smith & Johanson 2003 (Science)
4. Long 2006 (Nature)
5. Long et al 2008 (Nature)
6. Long et al 2009 (Nature)
7. Ahlberg et al 2009 (Nature)
8. Rucklin et al 2012 (Nature)
9. Trinajstic et al 2013 (Science)
10. Long et al 2014 (Nature)

TOTAL Impact factor points added as scored by system defined above= 611.

TOTAL pages published (peer-reviewed papers only) –c (less popular books) = 4389pp.

*Including popular books featuring a lot of Gogo material: Rise of Fishes 2nd ed. 288pp, Dawn of the Deed, 278pp. Rise of Fishes 1 (188pp), Swimming in Stone (320pp) = 4384 plus 1074 = 5458 pp.

TOTAL citations, google scholar = 4009 citations.

Gogo Site h factor =33

Papers with citations=>32

1. Andrews et al 2006 (cn=34); 2. Campbell Barwick 1983 (cn=41); 3. Campbell, Barwick 1987 (cn=87); 4. Campbell, Barwick 1988b (cn=37); 5. Dennis Miles 1979a (cn=36); 6. Dennis Miles 1981 (cn=43); 7. Dennis-Bryan 1987 (cn=64); 8. Druce 1976 (cn=77); 9. Gardiner 1973 (cn=57); 10. Gardiner 1984 (cn=250); 11. Gardiner & Bartram 19977 (cn=39); 12. Glenister 1958 (cn=51); 13. Glenister, Klapper 1966 (cn=124); 14. Long 1995 (cn= 121); 15. Long 1997 (cn=36); 16. Long et al. 1997 (cn=64); 17. Long et al 2009 (cn=40); 18. Long et al. 2008 (cn=52); 19. Long et al. 2006 (cn=66); 20. Marshall et al.1986 (cn=39); 21. Miles 1971 (cn=80); 22. Miles 1977 (cn=188); 23. Miles Dennis 1979 (cn=45); 24. Miles & Young 1977 (cn=55); 25. Nazarov et al. 1982 (cn=48); 26. Nicoll 1977 (cn=42); 27. Rosen et al.1981 (cn=392); 28. Smith 1977(cn=48); 29. Smith 1979 (cn=48); 30. Young 1984 (cn=43); 31. Young 1986- 94; 32. Sanchez et al 2012 -33; 33. Trinajstic et al 2007- 34

BIBLIOGRAPHY OF GOGO FOSSIL PAPERS

Not inclusive of primarily geological papers. As mentioned above, the list below contains primary references on Gogo fossils, major review papers on Gogo fossils, plus peer-reviewed papers illustrating Gogo specimens to assist with morphological interpretation of other materials.

Ahlberg PE. 1989. Fossil fishes from Gogo. *Nature* 337, 511-512. (IF=42, cn=6, pp=3).

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PART B: POPULAR PUBLICATIONS CITING GOGO FISHES

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