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Antipodean Ice Ages

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ABSTRACT

Recognition of vanished glaciation in the Southern Hemisphere dates back to the 1820s, but major interest dates from the 1850s. In 1852 Rev. W. B. Clarke suggested that Pleistocene glaciation had affected the Australian Alps. Studies by F. von Hochstetter and J. von Haast, from 1859, recognised active glaciation in New Zealand. The extraordinary valley glaciers which dropped from elevations of 2 500 m to 150 m above sea-level, bordered by forests of tree ferns, caused international interest. Hochstetter noted the existence of similar glaciers in South America and postulated that the Southern Hemisphere was still experiencing an Ice Age, while that in the Northern Hemisphere had ceased. Hochstetter was, however, more impressed by the evidence of vanished glaciation on a much larger scale. Identification of a glaciated surface in the Inman Valley of South Australia by A. R. C. Selwyn in 1859 marked the beginning of certain knowledge of glaciation in Australia. In 1877 studies at Halletts Cove in South Australia by R. Tate began a systematic examination of Australian glaciation. Tate, like those before him, believed the glaciation was "Newer Tertiary", (but it was later recognised as Late Palaeozoic). However many geologists were sceptical that glaciation could occur at such low latitudes, and close to sea-level, despite the New Zealand evidence. Glacial features studied by Selwyn and R. Daintree at Bacchus Marsh, and elsewhere in Victoria, in the 1860s, after early scepticism, were attributed to a Late Palaeozoic event, and its greater extent was recognised through the 1880s. In 1885 R.D. Oldham suggested contemporaneity between this glaciation and those recognised in India and South Africa. The Pleistocene record began to be studied in the Australian Alps in the 1880s by R. von Lendenfeld, who also examined the New Zealand glaciers. Lendenfeld pointed out that no satisfactory theory of the reason for ice ages could be accepted unless it took into account glaciations in the southern hemisphere. A major contributor to research on both the Pleistocene and late Palaeozoic glaciations was T. W. E. David, who directed a Glacial Committee under the auspices of the Australasian Association for the Advancement of Science, which gathered evidence from researchers throughout Australia and New Zealand. The information gathered on the late Palaeozoic glaciation was a major source of evidence to support Wegener's theory of continental drift and the existence of a long vanished Gondwana supercontinent. A Late Precambrian event (originally thought to be Cambrian) was recognised from 1900, through W. Howchin. Later studies expanded the extent of the ancient glaciations to NW Australia. Australian glacial studies played an important role in the development of knowledge of Gondwanaland, and more recently of the concept of Rodinia.

ZUSAMMENFASSUNG

Spuren verschwundener Vereisungen in der Südhalbkugel wurden schon in den 1820er Jahren erkannt, fanden jedoch erst in den 1850ern grössere Beachtung. Rev. W. B. Clarke vermutete eine pleistozäne Vereisung der Australischen Alpen. F. v. Hochstetter und J. v. Haaste entdeckten 1859 die aktive Vereisung auf Neuseeland. Die aussergewöhnlichen Talgletscher, die von 2.500 m bis auf 150 m über dem Meeresspiegel hinabreichten und von Wäldern aus Baumfarnen gesäumt waren, fanden internationales Interesse. Hochstetter bemerkte das Vorhandensein ähnlicher Gletscher in Südamerika und postulierte, dass sich die Südhalbkugel noch in einer Eiszeit befand, die für die Nordhalbkugel bereits vorüber war. Hochstetter war jedoch noch mehr von den Beweisen für eine Vereisung viel grösseren Ausmasses beeindruckt. Die Erkennung einer Vereisungsfläche im Inman Valley Südaustraliens durch A. R. C. Selwyn 1859 markiert den Beginn der sicheren Kenntnis einer Vereisung in Australien. Mit R. Tate's Untersuchungen in Hallets Cove in Südaustralien 1877 begann eine systematische Erforschung der australischen Vereisung. Tate glaubte wie seine Vorgänger, dass die Vereisung "Jüngeres Tertiär" sei (aber sie wurde später als jungpaläozoisch erkannt). Viele Geologen blieben jedoch skeptisch gegenüber einer Vereisung in so niedrigen Breiten und in einer so geringen Meereshöhe, trotz der Beweise in Neuseeland. Nach urpsrünglicher Skepsis wurden Vereisungsspuren, die von Selwyn und R. Daintree in den 1860er Jahren bei Bacchus Marsh und anderswo in Victoria untersucht wurden, einem jungpaläozoischen Ereignis zugeordnet, dessen grössere Ausdehnung in den 1880ern erkannt wurde. 1885 vermutete T. Oldham Gleichzeitigkeit dieser Vereisung mit denen von Indien und Südafrika. Die pleistozänen Vereisungsspuren in den Australischen Alpen wurden von R. v. Lendenfeld in den 1880er Jahren erforscht, der auch die neuseeländischen Gletscher untersuchte. Lendenfeld betonte, dass keine befriedigende Erklärung für Eiszeiten ohne eine Berücksichtigung der Vereisungen der Südhalbkugel möglich sei. Wichtige Beiträge zur Erforschung der pleistozänen und der jungpaläozoischen Vereisung wurden von T. W. E. David geleistet, der ein Glacial Committee der Australasian Association for the Advancement of Science leitete, das die Ergebnisse von Forschern aus Australien und Neuseeland sammelte. Die auf diese Weise vereinigte Information bildete eine wichtige Stütze für Wegener's Theorie der Kontinentalverschiebung und die Existenz eines längst verschwundenen Superkontinents Gondwana. Ein jungpräkambrisches Ereignis (ursprünglich als kambrisch angesehen) wurde nach 1900 von W. Howchin erkannt. Spätere Untersuchungen erweiterten den Bereich der alten Vereisungen auf NW Australien. Die australische Glazialforschung spielte eine wichtige Rolle bei der Entwicklung des Konzepts vom Gondwanaland, und in neuerer Zeit auch von dem von Rodinia.

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Fig. 1. Significant localities in the history of glaciation in Australasia.

1. Introduction and First Notions

"To look for glaciers one must go up the mountains, not down to the sea" wrote Robert von Lendenfeld (1886a), zoologist and geomorphologist, briefly in Australasia (1881–86). He was, based on his European experience, quite right, but he was, in Australia at least, profoundly wrong.

Recognition of vanished glaciation in the Australasian region of the Southern Hemisphere (Fig. 1) dates back to the 1820s (Branagan 1972). The evidence comes from a report by Captain Thomas Raine, who had visited Macquarie Island between Australia and Antarctica in 1821. Raine wrote to Edward Wollstonecraft January 1822 "On top of the island are many lakes.... probably glacial... evidence everywhere that the island has been covered by ice in the past". Banks et al. (1987) suggest that the real observer was Dr. David Ramsay, a business partner of Raine, and with a medical degree from Edinburgh, where both Hutton and Playfair had accepted the reality of glaciation. The initial report was edited in Sydney and published there on February 4 1822. Governor Thomas Brisbane communicated the report to the Royal Society of Edinburgh (Brisbane 1824) but it does not appear to have attracted much attention among geologists.

Charles Darwin, examining (Permian) marine rocks containing "few rounded pebbles" near Hobart, Tasmania in 1836, wrote a memorandum about the "resemblance between the older strata and the bottom of the sea near T. del Fuego", where he had previously recorded the action of sea ice depositing such blocks (Banks et al. 1987). However he never published these comparisons. Darwin (1845) also made an interesting comparison with European conditions by taking the Northern Hemisphere equivalent latitude, and considering how glaciation would have operated there.

Joseph Milligan (1849) interpreted a granite boulder in weathered Permian rocks near Southport, Tasmania, as due to "glaciers, and or, which is more probable, icebergs". Milligan came from Dumfries, Scotland where William Buckland in 1840 had noted moraines, and he may have also been influenced by his contact with Robert Jameson.

The second round the world voyage led by Dumont D'Urville, particularly to the southern polar seas, lasted from 1837 to 1840, but publication of the results was spread over

Fig. 2. Sketch of the Tasman Glacier by J von Haast (c. 1863) (Hochstetter Papers, Geological Survey of Austria, Vienna)

more than 15 years. J. Grange, medically trained (but also knowledgeable in geology), was one of the savants on the voyage, and to him was assigned the task of writing up the geology observed. The results appeared in two volumes (Grange 1848, 1854). In the first volume Grange gives considerable attention to the glacial geology of the Antarctic region and Patagonia, with particular concentration on sea ice and icebergs. This work certainly helped to draw attention to Southern Hemisphere glaciation and Grange showed he had studied the works of de Saussure, Hugi, Venetz, Charpentier, Agassiz and Forbes, as well as Darwin on Patagonia, although much of this knowledge was acquired on his return from the voyage. However the voyage did not include a visit to the glaciated regions of New Zealand and no thought appears to have been given to the possibility of glaciation in Australia.

2. New Zealand

Both James Cook and J. R. Forster (Beaglehole 1955; Hoare 1976) considered the distribution of sea ice in the Southern Ocean, and recognised that some large ice floes could be derived from land ice sources, but they paid little attention to the specific matter of glaciation. Although Cook, on several occasions from 1770, and other navigators, had visited the fjords of southwest New Zealand, there are few or no comments on the features left by vanished glaciers. In fact, no observations of significance concerning New Zealand glaciation were made until Ferdinand von Hochstetter, released from his post on the "Novara" Expedition, carried out his classic fieldwork over nine months in 1859. Hochstetter believed that the effects of glaciation were largely restricted to the (present) South Island, where he described five great valley glaciers radiating from Mt Cook, but he suspected that glaciation might have affected the Mt Ruapehu region in the North Island, which the Maoris had pronounced tapu, and could not then be investigated (Hochstetter 1864). Hochstetter compared glaciation with that of far South America, and he considered quite firmly that an Ice Age, similar to that which had affected Europe, still persisted in the Southern Hemisphere, particularly in New Zealand. But he affirmed also that "more gigantic glaciers previously existed", evidence being given by the remains of terminal and lateral moraines and roches moutonées that were preserved, 1 000 ft above the present valley floor of the Tasman River.

A fortunate event was the meeting of Hochstetter with a recently-arrived German migrant, Julius (von) Haast. Several years older than Hochstetter, Haast became, in effect, Hochstetter's field assistant and rapidly learnt geology under his tutelage. Haast noted that the Franz Josef Glacier (as it was later named) descended to 500 ft above sea-level and that tree ferns grew at its margin. Both Hochstetter and Haast were originally supporters of a mixed drift-floating ice theory to explain much of the geology of the South Island, which Haast then believed had been submerged. Haast later changed his ideas, accepting a widespread surface glaciation. James Hector, who had encountered glaciation in the Canadian Rockies, on being appointed Provincial Geologist for Otago, made a visit to the Southland fjords in 1863, with the botanist and artist John Buchanan. Hector, and F. W. Hutton (1875) also, were inclined to feel that the earlier glaciation was the result merely of the mountain ranges being higher, although Hector was somewhat equivocal on this matter.

Haast's first major paper on glaciation was read at the Royal Geographical Society of London on 8 February 1864, and was published in the society's Vol 34 with other papers on New Zealand geology by Hector and James McKerrow, anoth-

Fig. 3. Striated surface, Inman Valley, South Australia (Photo by W. Howchin, David Papers, University of Sydney)

er mountain explorer. As H. v. Haast (1948, 331) points out Julius Haast "never lost sight of that more appreciative audience that awaited him in Europe". Haast gained even more publicity by commissioning the artist John Gully to paint scenes from v. Haast's sketches (Fig. 2) (Gully also went into the field) and these were widely acclaimed when exhibited in London. J. D. Hooker wrote to Haast to congratulate him on his research, although downgrading things a little by noting he "hate[d] the claptrap and flummery of the Royal Geographical with its utter want of Science and craving for popularity and excitement, and making London Lions of the season of bold Elephant hunters and Lion slayers, whilst the steady slow, and scientific surveyors and travellers have no honours at all. You were right, however, to send your views there, as they were best exhibited and most extensively shown. I have asked Murchison to lend me the 'Hooker Glacier' for my father to see. He has promised to do so." (H. v. Haast 1948).

Hochstetter postulated successive periods of uplift, depression and subsequent uplift to explain the features he saw, but his sequences, accepted at first by his protegé, were later discarded by Haast. Despite Haast stating that his ideas on New Zealand glaciation were the result only of his own field observations, Oldroyd (1973) makes a good case that the letters and publications of European researchers, particularly A. Ramsay, J. Tyndall and R. Murchison were extremely influential. Belt (1877) discussed the evidence produced by various geologists on South American and New Zealand occurrences and came out firmly that the Pleistocene glaciations of the Southern and Northern Hemispheres were essentially contemporaneous.

Although there was plenty of cross-fertilisation of ideas between Australian and New Zealand geologists the study of glaciation in the two countries became more independent from this time on, and only a brief mention will be made in this paper on later New Zealand work, the concentration being on Australian studies.

3. The Kosciuszko Region, Australia

Major Australian interest in the phenomenon of glaciation dates from the 1850s when Rev. W.B. Clarke first suggested that Pleistocene glaciation might have affected the Australian Alps. Clarke, returning from a government-funded search for gold, made the arduous climb from the south to the Kosciuszko Range (Australia's highest region), named in 1840 by the Polish geologist P.E. Strzelecki and visited even earlier by another Polish naturalist, John Lhotsky (Branagan 1986; Vallance 1977). Clarke had studied geology with Rev. Adam Sedgwick at Cambridge, and had been inspired when visiting the Swiss Alps in the 1820s to write a bad poem about the scenery, emigrating to Australia in 1839. He noted (March 1852) "....probably in earlier times glaciers did form, for I saw more than one unmistakeable *bloc perché*, a mass resting on upturned edges of strata." However his observations were not published until 1860 (Clarke 1860: 225).

This region was difficult of access and Clarke and other geologists were busy with the search for coal and gold and the sorting of stratigraphic problems. Thus, despite his continuing activity as a geologist for the next 25 years, Clarke never revisited the Australian Alps, or took up the question of glaciation to any serious degree, although after W.A. Tully, following an expedition to western Tasmania (1858–9), reported quartz and greenstone "drift" of two ages, Clarke suggested that the drifts were local and "probably are partially moraines, the product of snow and ice of a colder epoch than at present" (Banks et al. 1987).

Charles Gould, Geological Surveyor of Tasmania, visiting the same area of western Tasmania in 1860, observed greenstone (dolerite) boulders in the Cuvier Valley. He thought an "enormous accumulation of boulders which chokes the lower end of the valley, and somewhat like a dam, extends completely across it" was possibly a terminal moraine (Gould 1860). However, because he did not observe polished, grooved or striated surfaces he was loth to invoke glacial action (Johnston 1893).

Some knowledge of the Australian Alpine region was spread through reports of the expeditions of the botanist, Ferdinand von Mueller in 1855, and the meteorologist Georg Neumayer in 1862. The Austrian-born artist Eugene von Guérard, with considerable geological interests, who accompanied Neumayer, painted at Mt. Kosciuszko what has become an icon of Australian art. Another artist who made the highlands of Australia and New Zealand well-known was Nicholas Chevalier, born in Russia of a Swiss father.

4. The Inman Valley, South Australia

Identification of a glaciated surface in the Inman Valley of South Australia (Fig. 3) by A. R. C. Selwyn in 1859 marked the beginning of certain knowledge of glaciation in Australia. Selwyn (1860) stated "this is the first and only instance of the kind I have met with in Australia." Selwyn, educated at school in Switzerland, where he gained his enthusiasm for geology and mountain climbing, had come to Australia in 1852 from some years intensive fieldwork for the Geological Survey of Great Britain. He had worked in North Wales with A. Ramsay, under H. De La Beche, in the 1840s, during the debates about glaciation which split the British geological community. De La Beche clearly opposed Agassiz, Buckland and Lyell, and was supported in his denunciation by W. Conybeare and G. B. Greenough in the early 1840s, but he gradually came around to accepting glaciation. Whether Ramsay (1852), and to a lesser degree Selwyn, were influential in changing his mind is uncertain, but De La Beche's visits to their glaciated field areas in North Wales must have played a part. Certainly Selwyn had no doubts when he made his own observations in a surprising region, the Inman Valley of South Australia in 1859.

The Inman Valley site is only 150m above sea level and less than 20 km from the sea. Naturally, at the time, Selwyn assumed that the glaciation was Pleistocene. Like Clarke in 1852, Selwyn was unable to pursue the matter, as he had to return to his official duties in Victoria. Selwyn's observations were published in 1859 and more widely the following year. Selwyn's identification was supported in 1867 by Rev. J. E. Tenison Woods.

However it was not until 1877 that careful studies at the seashore site of Halletts Cove in South Australia by R. Tate began a systematic examination of Australian glaciation. Tate, like those before him, believed the glaciation he recognised there was "Newer Tertiary". However many geologists were sceptical that glaciation could occur at such low latitudes, and close to sea-level, despite the New Zealand evidence of present glaciation.

Glacial features, including loosely consolidated gravels with striated boulders, studied by Selwyn and R. Daintree at Bacchus Marsh, 40 km west of Melbourne, and elsewhere in Victoria, in the 1860s, after early scepticism, were attributed to a late Palaeozoic event, although plant fossils, identified as *Gangamopteris* by Frederick M'Coy were dated by him as Mesozoic (Daintree 1866; Selwyn 1866). The possible greater extent of this event through New South Wales and Queensland was realised by R. L. Jack (1879) and through the 1880s by C. S. Wilkinson, T. W. E. David, and others (David 1895). Interestingly the important Halletts Cove occurrence was not recognised as also being late Palaeozoic until 1893.

In 1885 R. D. Oldham, of the Geological Survey of India, visited Australia, and in company with Wilkinson and David visited sites in the Hunter Valley, north of Sydney. Oldham was convinced beds at Branxton were glacial in origin, were correlateable with the beds at Bacchus Marsh in Victoria, and resembled closely Talchir Beds of the Indian Permo-Carboniferous and were probably of the same age. The age contemporaneity suggested by Oldham (1886) was clouded by some uncertainty about the ages of rock successions in the separate regions, and by suggestions about other possible glaciations (e.g. in the Triassic, by Wilkinson (1879), later discounted). However the remarkable similarity, not just in unique beds of glacial origin, but in the sequences spanning the Late Palaeozoic-Mesozoic boundary, was an important one in strengthening the idea of Gondwana(land) first postulated from India by Blanford (1875), and supported by the palaeobotanical work of Feistmantel (Haubelt 1994), although Blanford and Feistmantel did have their scientific disagreements.

The same problems of origin assailed workers in South Africa, but in 1868 P. C. Sutherland asserted confidently that some conglomerates (of supposed Late Palaeozoic age) were of glacial origin. E. J. Dunn, who arrived in South Africa from Victoria in 1871 took up the story in his 1873 map of South Africa, and later contributed to a considerable amount of the research on glaciation when he returned to Australia in 1886 (Dunn 1894). About this time Feistmantel, on the basis of the fossil plants correlated the Bacchus Marsh beds with the Dwyka Conglomerate of South Africa. Broader aspects of the Gondwana glaciation are discussed by Meyerhoff & Teichert (1971), who suggest that it was Suess (1888) who first added Australia to Blanford's original "Indo-Oceanic continent" to which Suess (1885) gave the name Gondwanaland. But by 1901 Suess apparently had some doubts about whether Australia had been part of the supercontinent.

5. The Australian Pleistocene

Greater attention to the Australian Pleistocene record began to be given in the 1880s thanks to the Austrian R. von Lendenfeld. Lendenfeld, although remembered largely for his zoological work, was interested in landscape and specially glaciation. He visited (between 1881–1886) the New Zealand glaciers (Lendenfeld 1883, 1885b, 1889) and the Australian Alps (Lendenfeld 1885a, 1885c, 1886a, 1886b, 1886c). In New Zealand he made contact with Haast and ventured into the mountains, sketching, photographing and noting the salient glacial features, particularly the Hochstetter Dome, one of the many glacial features graced by the names of prominent geologists (mostly British and continental Europeans, although Clarke and other Australasians were also honoured).

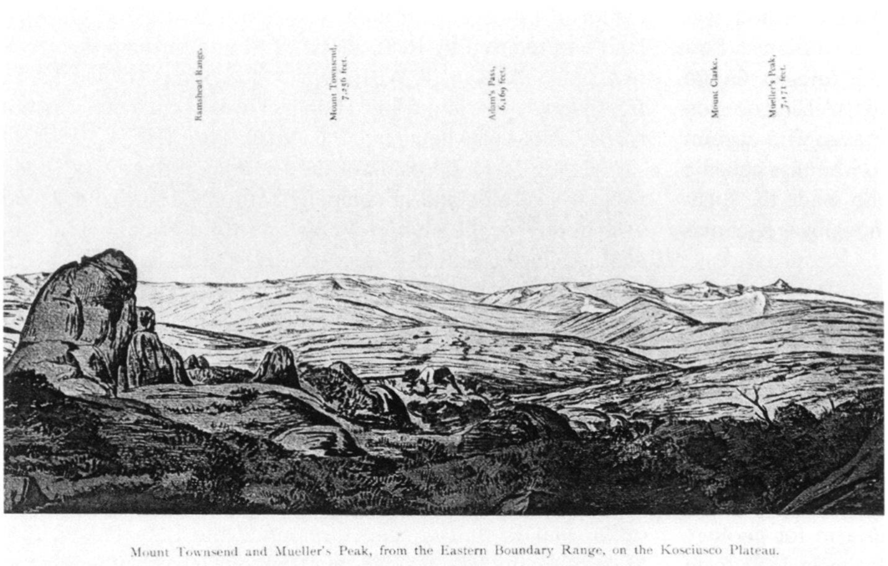


Fig. 4. Kosciuszko glaciation (sketch by Lendenfeld, 1885)

With funding from the New South Wales Government Lendenfeld spent some time in 1885 in the Kosciuszko region (Fig. 4), documenting the glacial features and quickly producing an impressive report, lavishly illustrated with sketches and photographs (Lendenfeld 1885a). He also visited the more southerly Bogong High Plains in Victoria, accompanied by Government Geologist James Stirling (Lendenfeld & Stirling 1887). Lendenfeld claimed evidence (including roches moutonnées and a well-preserved moraine at Mountain Creek) for glaciation in the area N of Mt Bogong. Lendenfeld's somewhat disdainful statement which prefaces this paper (Lendenfeld 1886a) was directed at what he regarded as a ridiculous claim, that there was evidence of glaciation at sea-level at Hallett's Cove, but he never visited the site. He suggested that the erratics found there were merely dumped by floating sea-ice coming from Antarctic waters when there might have been a colder period. Nevertheless he accorded credence to glaciation in the Mt. Lofty Ranges near Adelaide, South Australia, and discussed the possibility of glaciation in Tasmania (Lendenfeld 1886c). Lendenfeld's ideas were presented to the Geological Society of London by W.T. Blanford in 1885 (Lendenfeld 1885c) but the response was rather negative, the feeling being that the evidence was rather thin. J. B. Jaquet of the New South Wales Geological Survey who visited the Kosciuszko area was also a little sceptical of some of Lendenfeld's evidence (Jaquet 1897). However Helms (1893) and David et al (1901) provided a strong positive case for the Pleistocene event in the alpine region.

In his paper in *Nature* (Sept 30, 1886) Lendenfeld pointed out that no satisfactory theory of the reason for ice ages could be accepted unless it took into account glaciations in the southern hemisphere. He felt that New Zealand and Patagonia were still in a glacial period (unlike the Northern Hemisphere at a similar latitude, 44°), but that the New Zealand event had been even more extensive in the past. Obviously unaware of the literature Lendenfeld thought there had been no positive statements about definite Australian glaciation.

Lendenfeld claimed, erroneously, that a glacial period in Australia had been dismissed by local geologists, but he was correct in that there had been no serious examination of the alpine area of Australia to the mid 1880s. Lendenfeld thought the Australian and New Zealand glaciations were contemporaneous, but, unlike Belt (1877), could not correlate them with European events, thinking that the New Zealand-Australian event was possibly earlier than the last European glaciation.

Despite its quite southerly location, surprisingly little study of glaciation was carried out in Tasmania until the 1890s, when good evidence was found of extensive glaciation, extending down close to sea-level (Johnston 1893; Dunn 1894; Moore 1894). Permian glaciation was also recognised, with a component of marine floating ice, particularly in the south of the colony.

Probably the best summary of investigations of the Pleistocene to 1900 is given by David et al. (1901) although it is somewhat dismissive of Lendenfeld's work.

6. T. W. E. David

The major contributor to research on both the Pleistocene and late Palaeozoic glaciations (and later the Precambrian event) was undoubtedly T. W. E. David, who arrived in Australia in 1882, fresh from studies, and three publications, on the controversial topic of South Wales glaciation. Glaciation remained a major research project of David throughout his life. His enthusiasm was encouraged by the visit to Australia of R. D. Oldham mentioned above. At the inauguration of the Australasian

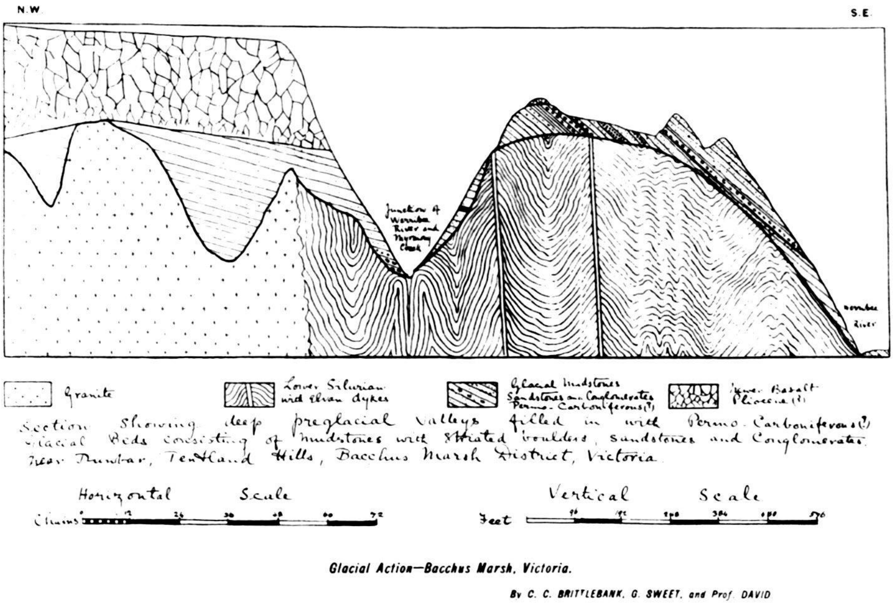


Fig. 5. Bacchus Marsh, Victoria, Cross-section, annotated by T. W. E. David (Brittlebank, Sweet & David, 1898)

Association for the Advancement of Science (AAAS, later ANZAAS) in Sydney in 1888 a committee to "investigate and report on Glacial Evidence in Australasia" was appointed with Tate as Secretary. The committee does not appear to have been very active initially, and at the Christchurch, New Zealand meeting in 1891, perhaps encouraged by research by J. H. Baker on the movement of marked stones on Mt Cook Glacier a committee "to investigate the movement of the New Zealand glaciers" replaced it. This committee also failed to report, and at the 1892 meeting in Tasmania a new committee "to report on the evidences of Glacial Action in Australasia during the Tertiary and Post-Tertiary" was appointed with Edgeworth David as Secretary. He remained Secretary and key-player, at the helm until his death in 1934.

The committee, which expanded its activities to consider evidence of any age, drew together reports from researchers in New Zealand and the various colonies of Australia, which were usually co-ordinated by David.

In 1893 AAAS held its fifth meeting in Adelaide and Tate took the opportunity to lead an excursion to Halletts Cove. This was the first chance for a large, relatively informed group to examine the site, and it was a great success. David also reported on research he had begun with colleagues (mostly amateur) to study the Bacchus Marsh area, in Victoria, (Fig. 5) in detail. The General Council of AAAS was so enthusiastic that it added new members to the Research committee and made a special grant of £20 to a local sub-committee (Secretary W. Howchin) "to be used for labour only in investigating the glacial phenomena at Hallett's Cove."

Only after this work was there a realisation among Australian geologists that Halletts Cove was a site of Late Palaeozoic glaciation. David's presentation at a Geological Society of London meeting, and the subsequent publication in the Society's Journal in 1896 marked the general acceptance by British geologists of an extensive Southern Hemisphere Late Palaeozoic glaciation, although David's paper of 1887 on the same topic had been less acknowledged. In his Presidential Address to the British Association in 1896 J. E. Marr commented: "as the result of the masterly résumé of Professor Edgeworth David the bulk of British geologists are prepared to admit that there has been more than one glacial period, and that the evidence of glacial conditions in the southern hemisphere in Permo-Carboniferous times is established."

David gained later fame, and practical experience of glaciation, by partaking in the Antarctic expedition of 1908–9 led by Ernest Shackleton.

7. Precambrian Glaciation – South Australia again

In 1885 H. P. Woodward, Assistant Government Geologist of South Australia, suggested that rock units (of probable Early Palaeozoic age) he mapped near the northern end of the Flinders Ranges of South Australia were possibly of glacial origin. However the idea became lost in an inaccessible Parliamentary paper. Government Geologist H. Y. L. Brown, Canadian-born, fourteen years later, also suggested ice transport was involved in the formation of similar sediments several hundred kilometres south of the site studied by Woodward.

In 1899 W. Howchin, working in Sturt Gorge, near Adelaide, and apparently unaware of either Brown's or Woodward's work (Cooper 1986), came to the conclusion that supposed Cambrian rocks were glacially-derived. Sensing the im-

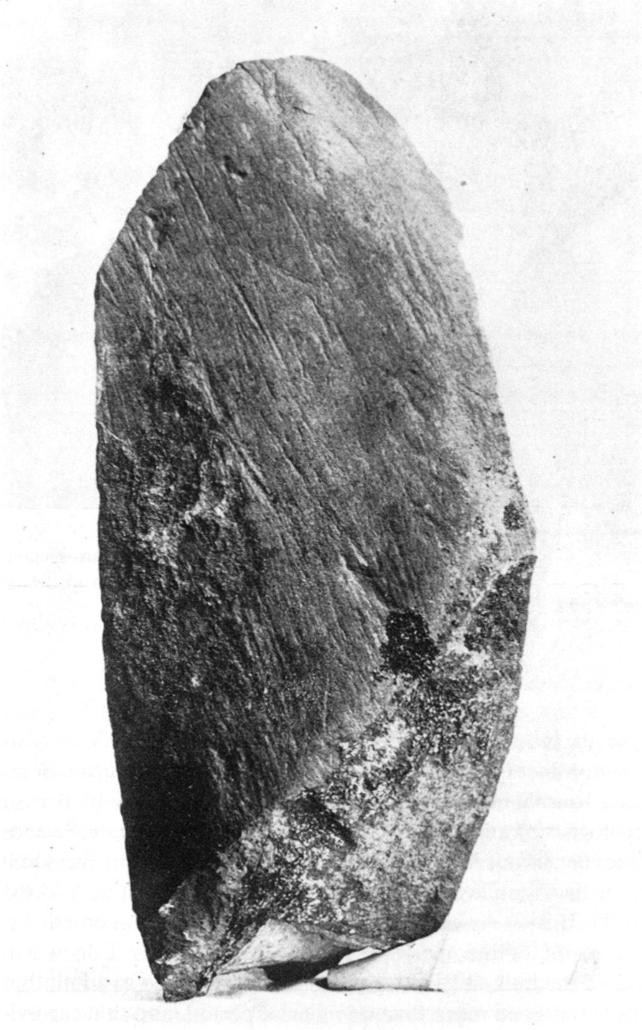


Fig. 6. Boulder from Precambrian glacial beds, Peterborough, South Australia (David, 1907)

portance of his ideas he published his findings in 1901, naming the unit Sturt Tillite (Howchin 1901, 1902). The work was publicised to a wider audience at the 1906 International Geological Congress in Mexico City by Edgeworth David (David 1907), who travelled to South Australia to examine the evidence, and who took large striated boulders (Fig. 6) among his luggage to Mexico, travelling via India to examine the evidence there for Late Palaeozoic glaciation. Howchin based his determination on the lithology of unstratified mudstones containing clasts of various lithologies varying in size from boulders to gravel pebbles. Not till some time later were striated boulders and pebbles discovered by Howchin. Howchin and others traced the extent of this glacial event (now known to consist of two quite separate tillite horizons) more than 700 km north from Adelaide and Douglas Mawson (1912) studied a similar succession in the Broken Hill region of New South Wales, a distance from Adelaide of about 350 km. Howchin's glacial interpretation was attacked by Herbert Basedow and J. D. Illiffe who argued that the tillites were misidentified, and the argument continued locally for about twenty years (Cooper 1986).

Howchin published a long paper in the Geological Society of London in 1908, and other papers overseas followed, particularly a long paper in the U.S. based *J. Geol.* (1912). Howchin was reluctant to pursue the world-wide implications of his work, although he later referred to some aspects of the matter (Howchin 1920), but this was taken up by Edgeworth David, who had begun the work in an addendum to Howchin's 1902 paper, and in 1939 Du Toit suggested a correlation of the Sturtian rocks with the Numees Tillite in South Africa.

As late as 1920 Howchin believed the glaciation to be of Cambrian age, but it is now established as occurring in the Neoproterozoic, and there were several distinct glacial episodes, with a considerable amount of material derived from floating ice (as Howchin believed). Later workers recognised similar glaciation in Tasmania (Brunnschweiler 1984).

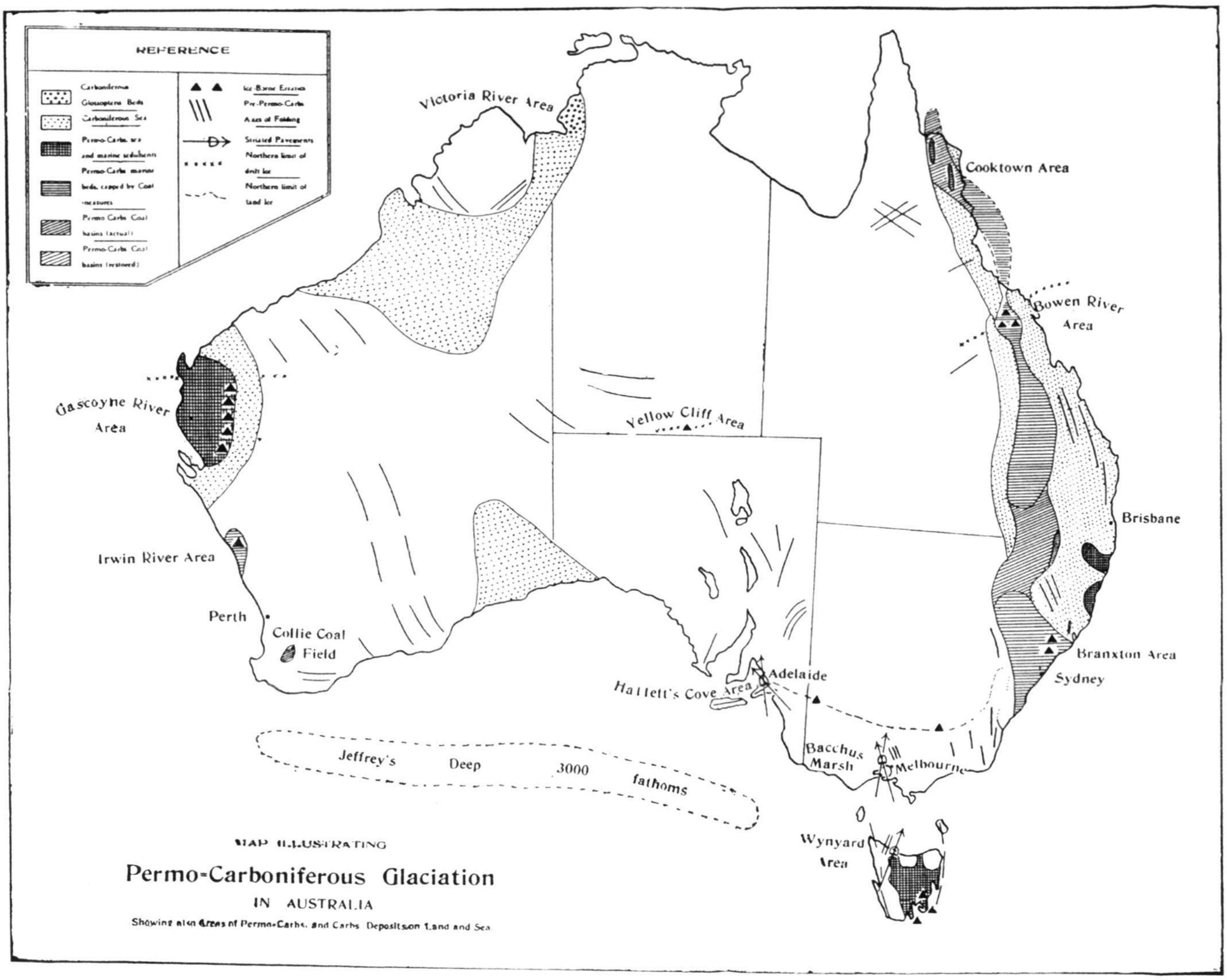
8. Expanding Horizons

Interest continued throughout the first half of the twentieth century, but can only be briefly mentioned here. A. G. Maitland (1911) and officers of his Geological Survey of Western Australia recognised the occurrence of the Late Palaeozoic glaciation in the Irwin River region, and further north around the Gascoyne River, and Maitland also expected evidence to be found in the Kimberley region comparable to the equatorial occurrences in India, which it later was. On the other hand Maitland was sceptical of Howchin's discovery of (supposed) Cambrian glaciation in South Australia, and only later were the extensive Late Proterozoic occurrences of the Kimberley and other Western Australian regions discovered (Brunnschweiler 1984).

A suspected Late Palaeozoic occurrence reported at Crown Point in (present) Northern Territory by Tate and J. A. Watt in 1894, and later by H. Y. L. Brown, was finally fully documented by David and Howchin in 1921 (David & Howchin 1923; Branagan 1981). They also suggested a younger (?Mesozoic) glacial event, but this has been generally discounted by subsequent work.

Major reviews, and significant studies, of the Late Palaeozoic glaciation include Süssmilch & David (1919), Osborne (1924), David & Süssmilch (1931), Campana & Wilson (1955), Wanless (1960), Crowell & Frakes (1971a, 1971b), O'Brien (1981), Cooper (1986) and Archbold (1998). Nevertheless, there have been periods of general neglect, and, in the 1960s in particular there was a episode of scepticism about evidence of glaciation, 'non-genetic' terminology being demanded for rock units, specially in the older successions, but the evidence has weathered the storm, and if leaner, today is healthily accepted, much as David suggested in 1906 (Fig. 7).

Comptes Rendus du X e Congrès Géologique International. Mexico 1906.



T. W. E. David. Conditions of Climate at different Geological Epochs. Plate F. (pags. 437–480).

Fig. 7. Late Palaeozoic glacial sites as presenteded by T.W.E. David, at the International Geological Congress, Mexico, 1906 (David, 1907)

In Tasmania and New Zealand the subtleties of Pleistocene glaciation continue to be studied, since the British Association meeting in Australia in 1914 recommended systematic recording in conformity with the Commission Internationale des Glaciers, and a committee on Cainozoic and Quaternary Climate was established by AAAS in the 1920s.

9. Summary

Glacial questions have interested Australian geologists for more than 150 years. Recognition of the Late Palaeozoic glaciation in Australia was a defining episode in the history of Australian Geology. The recognition of Late Precambrian glaciation, beginning as a supposed Cambrian glaciation, was likewise a very significant event. Knowledge of these glaciations provided important yardsticks for the concepts of Gondwanaland and, more recently, Rodinia (a Precambrian supercontinent). While Tate, Howchin and others made important contributions, Edgeworth David, as both field worker, enthusiast, organiser and publicist, was the major contributor to the development and spread of knowledge of Australian glaciation.

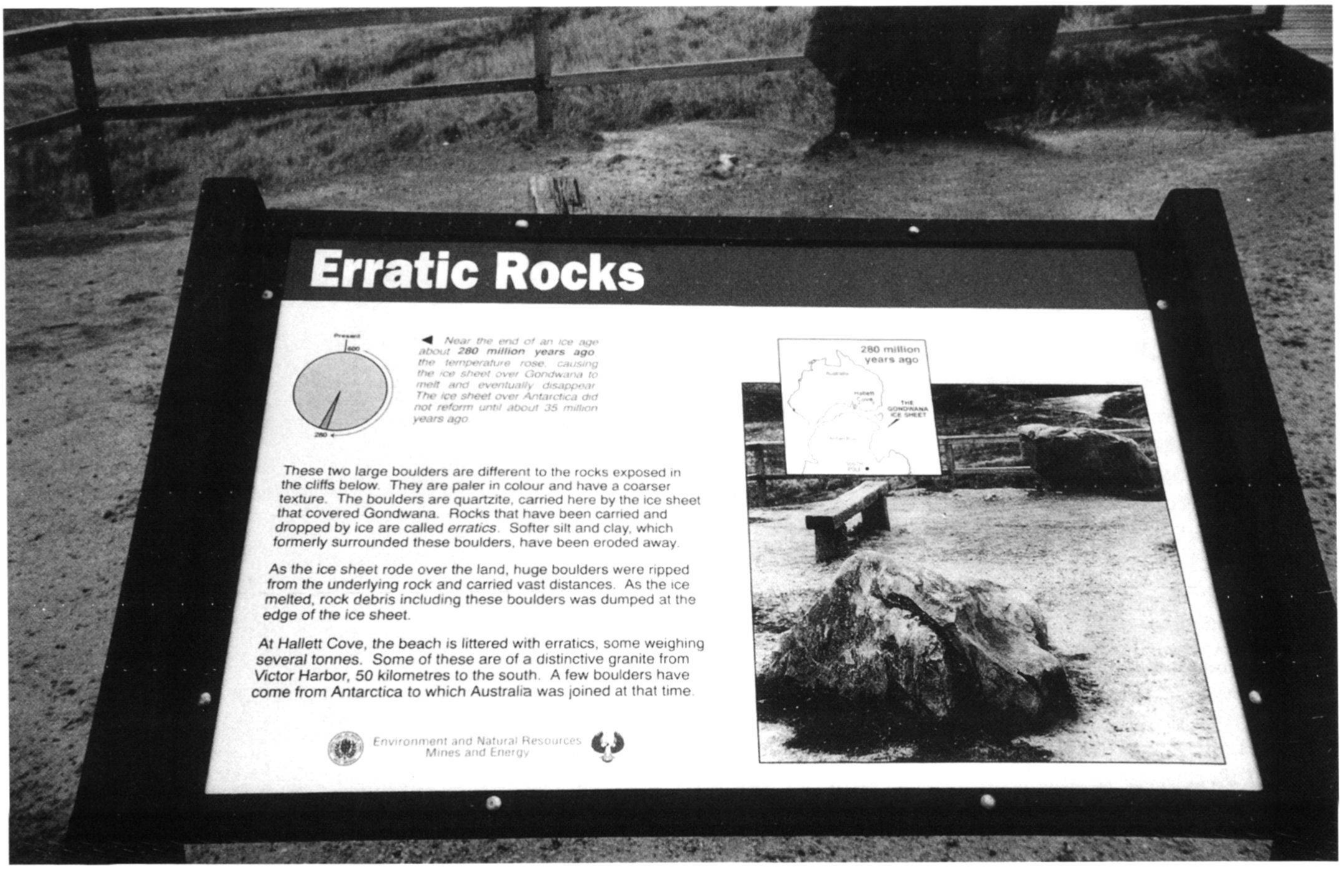


Fig. 8. Halletts Cove Geological Site, South Australia. One of the explanatory signs on this coastal reserve. (photo, D.F. Branagan)

Since David's time there has been a reassessment of the three glacial periods summarised by Howchin (1920) and discussed by Brunnschweiler (1984). The extent of Pleistocene glaciation on the Australian mainland was recognised as being more limited than David and his colleagues (particularly W.R. Browne 1952) had believed (Galloway 1963). Some of the features in the high country now rejected as Pleistocene, may indeed be preserved features of the Permian glaciation, which has left remnants of its extent across much of the continent, and which is being recognised as a major sculptor of the Australian landscape (Branagan 1989), as exemplified at Halletts Cove, now a special geological site (Fig. 8).

It is interesting, as Banks et al. (1987) have pointed out, that Clarke, Daintree, Selwyn and Gould were actively considering terrestrial glaciation as a significant geological phenomenon while it was still being strongly opposed by many leading British geologists. The determined pursuit of the field evidence and presentation of the evidence of the earlier glaciations in the latter part of the nineteenth century by David and his colleagues, while of major significance to the history of Australian geology, had broader, international implications for the history of geology.

The study of glaciation in Australia and elucidation of the story into three distinct episodes has been a continuing thread in the development of geological knowledge in Australia, and research continues to give new insights into Earth's history.

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