

'The most remarkable man': James Croll, Quaternary scientist

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ABSTRACT: The year 2021 marked the bicentenary of the birth of James Croll (1821–1890), the self-educated son of a crofter-stonemason, whose life was characterised by a dizzying range of occupations and homes, poor health and financial concerns, and yet he became a pioneer of orbital dynamics and ice age climate change with an impressive record of publication. Drawing upon archival information and recently published observations, this paper explores selected aspects of Croll's biography, his scientific connections and controversies, and that area of his life relevant to Quaternary science. He was a 19th century polymath whose multifaceted contributions have been a catalyst for subsequent systems-based climate science on the grand scale, including the foundations for the seminal work of Milutin Milankovitch on the rhythms of Quaternary environmental change.

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Introduction

Towards the end of November 1859, the naturalist Charles Darwin (1809–1882) published the first edition of *On the Origin of Species*. Two months later, James Croll, a clerk in the Glasgow office of *Commonwealth*, the temperance and socio-political reform newspaper, became the janitor of Anderson's University.¹ At this time, Croll, a crofter-stonemason's son from rural Perthshire, had left school at 13 years of age, trained as a millwright and considered himself a 'dull scholar' (Irons, 1896, p. 12). However, within 8 years, Darwin was to write to Croll:²

DOWN, BROMLEY, KENT

19th September 1868

DEAR SIR, I hope that you will allow me to thank you for sending me your papers in the *Philosophical Magazine*.³ I have never, I think, in my life, been so

deeply interested by any geological discussion. I now first begin to see what a million means, and I feel quite ashamed of myself at the silly way in which I have spoken of millions of years ... I thank you cordially for having cleared so much mist from before my eyes.

With sincere respect, I remain, dear sir, yours very faithfully,

CHARLES DARWIN.

Darwin was writing to a man who was later to reminisce (Croll, 1887, p. 14):

There were two important and, to most people, interesting sciences for which I had no relish, namely, chemistry and geology, more particularly the latter. The reason was that to me they appeared so full of details

¹In his *Autobiographical Sketch* (Croll 1887, p. 30) he claimed to have 'received the appointment and entered on my duties at the end of the autumn of 1859'. This is also the date universally repeated in accounts of Croll's life. However, the Minutes of Anderson's University indicate that the offer letter and acceptance both date to 1 February 1860; OB/1/1/4, p. 446. Anderson's University was a predecessor institution of the University of Strathclyde (Edwards, 2021b). Similarly, the application form in connection with examination and recruitment to the Geological Survey of Scotland indicate that he worked in the newspaper office of *Commonwealth* until 1860; The National Archives of the UK (TNA), Kew, CSC 11/73, Civil Service Commission. CROLL, James, file 89263, pp. 004, 005, 0017, 0018, 29 June 1867.

²DCP-LETT-6380; University of Cambridge, Darwin Correspondence Project. Transcribed in Irons (1896, p. 200).

³Believed to be Croll (1868a, b, c) as reported in Irons (1896, pp. 199–200), though with incorrect titles. The statement 'I now first begin to see what a million means' was referring to the following material from Croll (1868a, p. 375):

If we could possibly form some adequate conception of a period so prodigious as one hundred millions of years, we should not then feel so dissatisfied at being told that the age of the earth's crust is not greater than that.

Here is one way of conveying to the mind some idea of what a million of years really is. Take a narrow strip of paper an inch broad, or more, and 83 feet 4 inches in length, and stretch it along the wall of a large hall, or round the walls of an apartment somewhat over 20 feet square. Recall to memory the days of your boyhood, so as to get some adequate conception of what a period of a hundred years is. Then mark off from one of the ends of the strip 1/10 of an inch. The 1/10 of the inch will then represent one hundred years, and the entire length of the strip a million of years. It is well worth making the experiment, just in order to feel the striking impression that it produces on the mind.

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and so deficient in rational principles, being so much sciences of observation and experiment. Had any one told me then that one day I should be a professional geologist, I would have regarded the statement as incredible. In truth, it was more by accident than by choice that I became a geologist. Geology is Almost the only science on which ... I have never spent a single day's earnest study. However, the accident of becoming a member of the Geological Survey was of immense advantage to me when I afterwards became engaged in my climatological studies.

A review of Croll's monumental tome *Climate and Time in their Geological Relations: a Theory of Secular Changes of the Earth's Climate* (Croll, 1875a) was rapturous (Anon., 1875, p. 323):

The publication of this volume marks one of the great eras in the progress of geological investigation ... And when it is asked to whom science is chiefly indebted for this extension of its borders, who has made the most powerful and lasting impress on modern geological speculation, the answer undoubtedly should be – Mr. James Croll. No greater clearing of ground, lengthening of cords, and strengthening of stakes in the fields of geology have taken place since the days of Hutton; and while the Scotch may honour their Lyell, Murchison, Ramsay, and Geikie, they have the highest reason to be proud of their Hutton and Croll.

This was to find an echo in the final paragraph of the obituary produced by his Geological Survey colleague, John Horne (1848–1928) (1892, p. 181):

Of his private life it may be truly said that “whatever record leaps to light, he never shall be shamed;” of his career as a man of science it may be confidently asserted that he has nobly sustained the reputation of the Scottish School of Geology, which was founded by the genius of Hutton and Hall.

In his history of the Geological Survey of Great Britain, Edward Bailey (1952, p. 77) lauded Croll – ‘it is impossible to pass over his advent in silence, since he was the most remarkable man ever enrolled in the Geological Survey, in fact a prodigy’. Yet James Croll's life began inconspicuously, with a stuttering series of employments, before he experienced international scientific fame, only to fall back into relative obscurity.

The semi-popular and more scholarly analyses of Croll's scientific outputs have tended to concentrate on his astronomical and climatic deliberations, often preceded with summary statements on his humble beginnings, lack of schooling, and financial and health concerns (e.g. Alexander, 1900; Imbrie and Imbrie, 1979; Tasch, 1986; Farrow, 2001; Gribbin and Gribbin, 2001; Fleming, 2006; Hilgen, 2010; Finnegan, 2012; Sugden, 2014; Pearce, 2018; Dry, 2019). In the year following the bicentenary of his birth, and drawing upon archival records and recently published observations (Edwards 2021a), this paper explores selected aspects of Croll's biography, his scientific connections and controversies, and that area of his life relevant to Quaternary science. While presenting material that has often been ignored hitherto, the

paper does not set out to be encyclopaedic, and beyond contextualisation no attempt is made to explain at length the science with which Croll was engaged.

The passage of a life

Knowledge of James Croll (1821–1890; Fig. 1) benefited from the production of his short autobiographical essay (Croll, 1887) alongside a substantial volume of material collated by his solicitor friend, James Campbell Irons (1896). The *Autobiographical Sketch of James Croll: with Memoir of his Life and Work* is a somewhat adulatory account (cf. Edwards, 2021a; Edwards and Robinson, 2021), but the factual content and transcriptions of Croll's voluminous correspondence contained within it are reliable (Edwards, 2021b, c).

From croft to insurance salesman

Having grown up on a Perthshire croft and missing a great deal of schooling, Croll at age 11 began to self-educate, ‘with assistance from no one’ (Croll, 1887, p. 13), via the *Penny Magazine*, produced for the Victorian working classes by the Society for the Diffusion of Useful Knowledge (Secord, 2000). Two years later he left school to assist his mother on the croft and by the age of 16 he was apprenticed locally to a wheelwright, repairing corn-, saw- and threshing-mills, sleeping in lofts and burying himself under clothes ‘to secure protection from the rats’ (Croll, 1887, p. 16). Prior to his janitorial position, he had a range of other employments including joiner, tea merchant and shopkeeper, temperance hotelier and insurance salesman (‘the most disagreeable part of my life’ (*ibid.*, p. 29)) which took him as far south as Leicester – one of his relatively rare stints beyond Scotland (Table 1; Edwards and Robinson 2021).

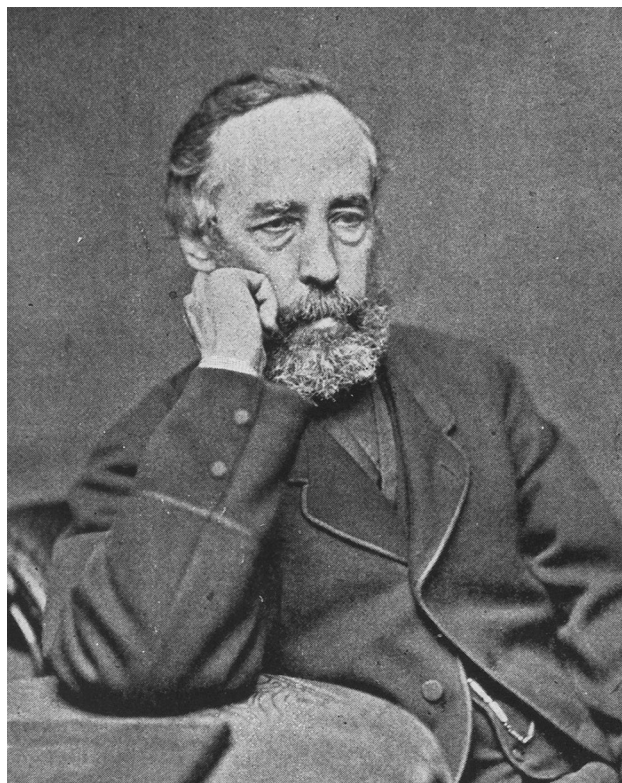


Figure 1. Portrait of James Croll from the frontispiece of Irons (1896).

Table 1. Key dates, locations and employments for James Croll.[†]

Year(s)	Locations	Status or occupation
1821	Little Whitefield, Perthshire	Birth, 2 January
1824	Wolfhill, Perthshire	School pupil
1837–1841	Wolfhill?, Perthshire	Apprentice millwright
1841–1842	Banchory, near Coupar Angus, Perthshire	Journeyman millwright
1843–1846	Wolfhill and Collace, Perthshire; Glasgow; Paisley	Joiner
1846–1850	Wolfhill/Perthshire; Elgin	Tea salesman; marriage to Isabella Macdonald of Forres, 11 September 1848
1850–1851	Wolfhill, Perthshire	Constructor of electrical induction apparatus for medical restorative purposes
1851–1852	Perth, Perthshire	Furniture maker for intended temperance hotel
1852–1853	Blairgowrie, Perthshire	Temperance hotelier
1853–1857	Glasgow; Dundee; Edinburgh; Leicester; Paisley	Insurance office
1857	Glasgow	Writer (<i>The Philosophy of Theism</i>)
1858	Glasgow	Newspaper office clerk (<i>Commonwealth</i>)
1860–1867 [‡]	Glasgow	Janitor, Anderson's University, writer
1867–1881	Edinburgh	Office keeper and geologist
1881–1890	Elgin; Cumbernauld; Dawlish; Perth; Hamilton; Bridge of Allan	Retired, though still writing
1890	Perth	Died, 15 December
1890	Cargill Churchyard, Perthshire	Burial, 18 December

[†]Extracted from a variety of sources, of which the principal ones are: British Geological Survey archives, Keyworth; Irons (1896), including Croll's Memoir of 1887; Civil Service Commission files (CSC 11/73) at The National Archives of the UK (TNA), Kew; Haslemere Educational Museum, Sir Archibald Geikie Archive; Imperial College London, Records of Thomas Henry Huxley; Minute book, Andersonian Library, University of Strathclyde, 1860; British Library (Add MS 41077), including the Royal Literary Fund (Loan 96 RLF 1/2220). Fuller source information is contained within Edwards (2021c) and Edwards and Robinson (2021).

[‡]Many commentators quote autumn 1859 as Croll's start date as janitor at Anderson's University. This follows his recollected date in the *Autobiographical Sketch* (Croll 1887, p. 30). The Minute book for the institution make it clear that he was appointed to the position on 1 February 1860. See footnote 1 for further detail.

During a pause in paid employment, he wrote and published anonymously *The Philosophy of Theism* (Anon., 1857) which 'attracted but little general attention'.⁴ In spite of some critical reviews (Finnegan, 2021), the book's production was extraordinary for someone of Croll's educational background. Importantly, it did not infringe his approach to science, as it sought to discern fundamental principles, rather than facts *per se*, as critical parts of scientific explanation.

Janitor

His time as janitor at Anderson's University was to represent the happiest work period of his life – 'I have never been in any place so congenial to me as that institution proved' (Croll, 1887, p. 30). With his duties often performed by his physically challenged younger brother David (1822–1876), who lived on the premises with James and his wife Isabella (née Macdonald; 1828–1913), Croll had 'a good deal of spare time ... for reading and study' (Croll, 1887, p. 31) and he certainly made good use of this and the ready access to an excellent scientific library. By May 1864, he had published 11 articles in areas as diverse as electrical current, heat, gases, tidal waves and the rotation of the Earth and moon (a topic 'which does not appear to have been noticed by physicists' (Croll, 1864a, p. 285)). Three months later, there appeared his landmark paper – 'On the physical cause of the change of climate during geological epochs' (Croll, 1864b; discussed below).

⁴Irons (1896, p. 30). Prior to this, in 1854, he had published two pamphlets – one on predestination under the designation of a 'moderate Calvinist' and another 'on the bearings of geology and astronomy on the creation of the world' (*ibid.*, pp. 83, 492).

Publication and notice

His outputs can be classified into broad systematic strands which are depicted numerically in Table 2. Many of the published items are multi- or interdisciplinary (e.g. astronomical, climatic, glacial and oceanographic) and any one publication may be represented in multiple categories. Accepting the broad-brush nature of the exercise, it is apparent that an early interest in the fundamental and applied aspects of physics was soon accompanied by contributions in those areas of science which have come to characterise Croll; namely orbital dynamics and the way these impact upon climate, the oceans and glaciology. Time is a key ingredient within this mix, and the various components are often dealt with in what we would view today as part of an Earth-system science perspective as can be discerned in both papers (e.g. Croll, 1864b, 1868a, 1878) and books (Croll, 1875a, 1885a).

By 1865, Andrew Crombie Ramsay (1814–1891), Professor of Geology at University College London and President of the Geological Society of London, was to write to James David Forbes (1809–1868), physicist, glaciologist and Principal at the University of St Andrews: 'I fancy that Mr Croll of Glasgow is at present engaged on a memoir on changes of climate in geological periods. I have a very high opinion of him, he is a singularly modest man, and I suspect is almost quite self-educated.'⁵ A little over a decade later, with *Climate and Time* published (Croll, 1875a), the University of St Andrews was to bestow upon him the honorary degree Doctor of Laws (LL.D.) (for which it charged a fee of 10 guineas, equivalent to perhaps £1000 today) and the Royal Society of London had elected him to its Fellowship. For Croll, now in his 55th year and office manager of the Geological Survey of Scotland in Edinburgh – a

⁵University of St Andrews, University Library Special Collections, Papers of James David Forbes: msdep7/Incoming Letters 1865/46 (a,b).

Table 2. Number of items published per annum (shaded) by James Croll. Each item has also been categorised as to major constituent subject areas.

Year	No. of published items	Philosophy	Physics/chemistry	Orbital dynamics	Glaciology	Oceanography	Earth-system science	Climate	Time	Geology/geomorphology
1890	2	1								1
1889	3	1	1		1				1	2
1888	0									
1887	1	1								
1886	0									
1885	2		1	1	2	1	1	2	1	2
1884	4		2	3	3	2	3	3	2	3
1883	4	1		1	2	1	1	1		
1882	0									
1881	0									
1880	3		2	1	1			1		
1879	6		2	2	2	1	2	2	1	1
1878	6		5	2	1	1	1	1		1
1877	1		1						1	
1876	3		3		1				1	
1875	7		1	2	1	6	1	1	1	
1874	5				2	4				
1873	0									
1872	8	1	2			7				
1871	5					2			2	3
1870	7				3	3				4
1869	4			1	1	1	1	1		
1868	3			2	3	1	3	1	3	3
1867	5		1	3	2	1	1	3		
1866	6			2	4	4	1	1		1
1865	3				3	3				
1864	5		3	2	1	1	1	1	1	
1863	1		1							
1862	5		5							
1861	1		1							
1860	0									
1859	0									
1858	0									
1857	1	1								

post to which he had been enticed by Archibald Geikie (1835–1924) – the year 1876 was arguably the zenith of his scientific life (Edwards 2021b). Croll's gratitude for the recognition conferred by the distinctions of FRS and LL.D. is reflected in his use of both post-nominals throughout his life, and even in death, as he specified their inscription for his tombstone (*ibid.*).

There were many contemporary references to Croll's research within the pages of such major outlets as the *Philosophical Magazine*, *Nature* and the *Geological Magazine*. In addition, three influential books provided a visible endorsement for the standing of Croll and his ideas: the first volume of the 10th edition of *Principles of Geology* (Lyell, 1867); the fifth edition of *On the Origin of Species* (Darwin, 1869); and the first edition of *The Great Ice Age* (Geikie, 1874).

Connections

In terms of appreciation, indeed patronage, Croll was very well connected, even if he eschewed learned societies and, as he confessed to his religious mentor James Morison, the 'cold materialistic atmosphere around scientific men' (letter dated 17 August 1876; Irons 1896, p. 312). A flavour of his academic associations with men of influence may be gleaned from his nomination to the Royal Society of London. The certificate of candidature (Fig. 2), with election on 1 June 1876 as one of 15 Ordinary Fellows for the year,

bears the signature of Charles Darwin as the first listed nominator and included a distinguished crop of additional supporters including John Tyndall (1820–1893) and William Thomson (later Lord Kelvin; 1824–1907). Six of his 17 supporters were, or were to become, knights or peers of the realm, two became politicians and others had roles within the Royal Society of London and were also Fellows of the Geological Society of London (x12) and the Royal Society of Edinburgh (x7).

Interestingly, Croll was never a Fellow of his national academy, the Royal Society of Edinburgh (Brassington, 2021; Edwards, 2021b), nor was he a Fellow of the Geological Society of London. Such omissions reflect a self-selecting lack of clubbability, although his non-membership of the Geological Society did not stop him being offered or accepting three of its prestigious awards.⁶

Croll's connections and correspondents were a strongly interconnected group. Such academic and friendship linkages were and are commonplace (*cf.* Barton, 1998, 2018; Birks, 2005; Edwards, 2018; Gamble, 2021), but the social status and diversity of Croll's contacts, brought about by his own polymathic, far-sighted interests and perhaps his modest persona, are striking (Figs. 3 and 4).

⁶Wollaston Donation Fund (1872), Murchison Fund (1876), Barlow-Jamieson Fund (1884). These awards are discussed in Edwards (2021b) and Edwards and Robinson (2021).

1876/08

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Certificate of a Candidate for Election.

(N.B. Directions for the filling up are given on the other side.)

(Name) James Croll

(Title or Designation) _____

(Profession or Trade*) Geological Survey of Scotland

(Usual place of Residence) Geological Survey Office, Edinburgh

Author of many original and valuable contributions to Geology & Physical Geography, of which the following may be named:—

- On the Physical Cause of Changes of Climate during Geological Epochs. Phil. Mag. Aug. 1864
- The Eccentricity of the Earth's Orbit. Phil. Mag. Jan'y 1866, Feb'y 1867
- Geological Time and date of glacial and Miocene periods. Id. May, Aug. Nov. 1868
- The Physical Cause of the Motion of Glaciers. Id. March 1869 Sept. 1870
- The Supposed greater Lops of Heat by the Southern Hemisphere. Id. Sept 1869
- Ocean Currents. Id. Feb'y March Oct. 1871; Feb'y 1874 March June 1874
- Change of Obliquity of Ecliptic: its effect on Climate. Id. June, August 1867
- Physical Cause of Sedimentation during Glacial Epoch. Id. April 1866. Phil. Mag. July Aug. 1874
- Boulder Clay of Caithness & Glaciation of North Sea. Id. May May June 1870
- Methods of Determining mean Thickness of Sedimentary Rocks. Phil. Mag. March 1871
- What determines Tides? the Fundamental Problem of Nature. Phil. Mag. July 1872
- Climate and Time in their Geological Relations. Ser. London 1875

being desirous of admission into the ROYAL SOCIETY OF LONDON, we, the undersigned, propose and recommend him as deserving that honour, and as likely to become a useful and valuable Member. Dated this 2^d day of December 1875

<p style="text-align: center;">From General Knowledge.</p> <p>Charles Darwin John Lubbock John Tyndall H. Charlton Bastian M.H.N. Story-Maskelyne Henry Woodward Andrew Scott Waugh</p>	<p style="text-align: center;">From Personal Knowledge.</p> <p>Andrew Ramsay John Evans Archibald Geikie William Thomson R. Grant Allen Thomson Robert Etheridge William Sharpey James Hector Edward Hull</p>
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Elected June 1/76

Send to the Society on the 27th day of January 1876

FROM GENERAL KNOWLEDGE

Name	Occupation
Charles R. Darwin	Naturalist, geologist
John Lubbock	Banker, politician, archaeologist
John Tyndall	Physicist, professor
H. Charlton Bastian	Physiologist, professor
M.H.N. Story-Maskelyne	Geologist, professor
Henry B. Woodward	Geologist, Keeper British Museum
Andrew Scott Waugh	Surveyor-general of India

FROM PERSONAL KNOWLEDGE

Name	Occupation
Andrew C. Ramsay	Geologist, professor
John Evans	Archaeologist, geologist
Archibald Geikie	Geologist, professor
William Thomson	Physicist, professor
Robert Grant	Astronomer, professor
Allen Thomson	Physician, professor
Robert Etheridge	Geologist, palaeontologist
William Sharpey	Anatomist, physiologist, professor
James Hector	Geologist, surgeon
Edward Hull	Geologist, professor

Figure 2. Certificate of candidature (upper portion of figure) for James Croll, courtesy of the Royal Society of London (Collections EC/1876/08). Further details on the nominators are provided in Edwards (2021a).

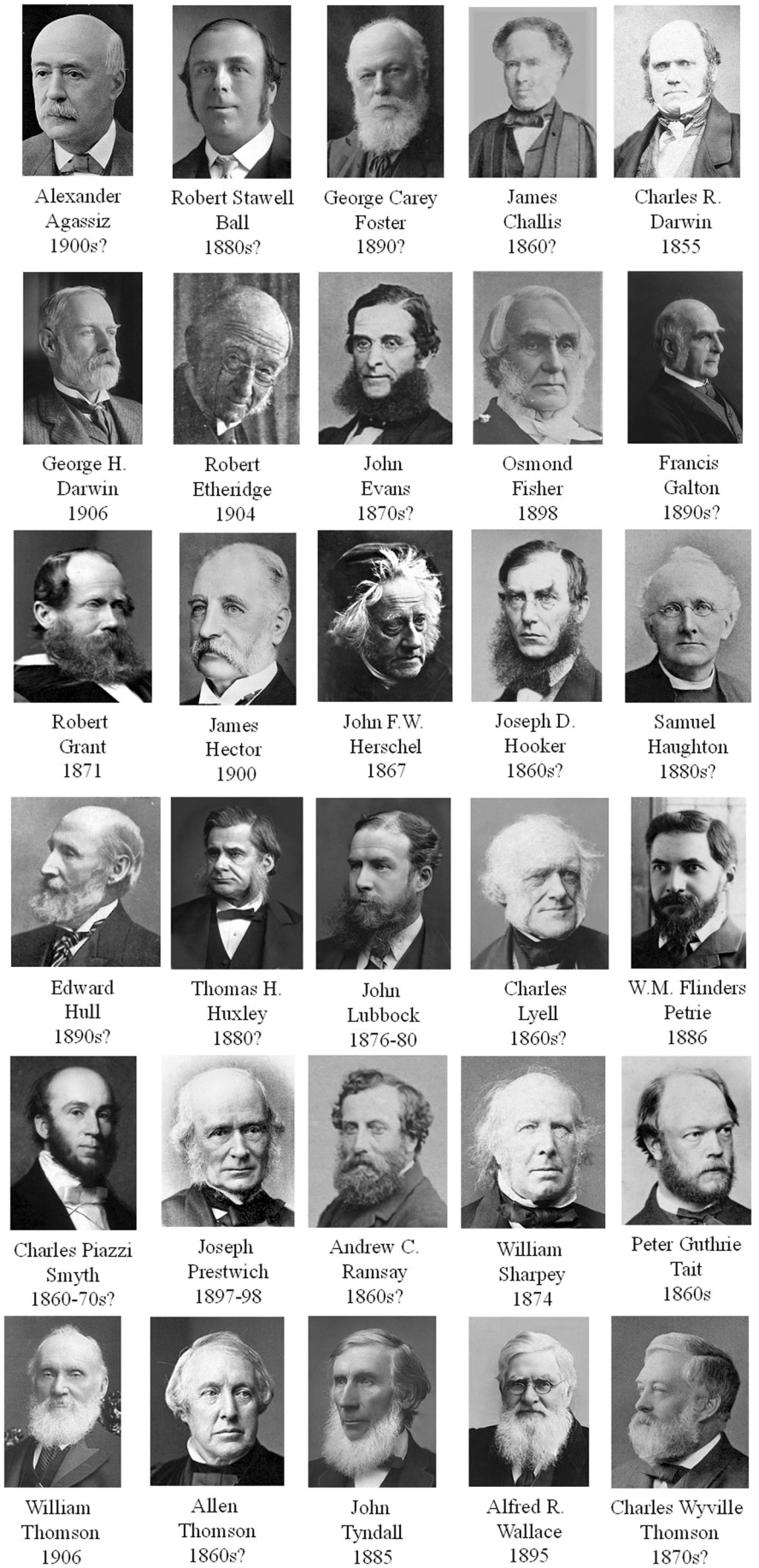


Figure 3. Some of the scientifically-inclined individuals with whom Croll corresponded (cf. also with Fig. 4) and was acquainted. Based especially on sources within the British Library, London (Add MS 41077 (in Western Manuscripts), letters from scientists to James Croll, biographer James Campbell Irons, and others, 1863–1898); the Royal Society of London (EC/1876/08, 27 January 1876, James Croll’s Certificate of Election); Irons (1896); and Edwards (2021b). All images in the public domain apart from those of Robert Grant (Digital image courtesy of the Getty’s Open Content Program) and Charles Wyville Thomson (courtesy of the Freshwater and Marine Image Bank at the University of Washington).



Figure 4. Picture of James Croll with other employees of the Geological Survey in Edinburgh, 1868. Standing left to right: James Geikie, John Horne, James Croll, C.R. Campbell, Ben Peach, Duncan Robertson Irvine, Harriman Malcolm Skae, and Robert Logan Jack. Seated: Edward Hull and Archibald Geikie. (Permit Number CP20/060 Photo P008752 Courtesy of the British Geological Survey Source: <http://earthwise.bgs.ac.uk/index.php/File:P008752.jpg>).

Disappointments: health, income and pension

Health and income were omnipresent aspects of Croll's life which exerted considerable negative influences on his conduct and thoughts.

Within the *Autobiographical Sketch* (Croll, 1887), the *Memoir* (Irons, 1896) and in various archival sources (Edwards, 2021c) there are numerous references to health issues. These mainly refer to symptoms associated with the head, heart and elbow joint, as well as problems with eyes, fatigue and other ailments. In 1865, the occurrence of a twitch in his head 'proved to be the severest affliction that has happened to me in life' and he felt that all the research work of the following 20 years would otherwise possibly 'easily been done ... in the course of two or three years' (Croll, 1887, p. 33). Croll's anguish deepened in 1880 when, in the Edinburgh office, he 'strained something about the region of the heart' which so debilitated him that 'As I was now disabled for duty both by head and heart ... it was considered advisable that I should resign' (*ibid.*, 39–40). We can only guess at his state of mind when observing that health issues and work tasks led him to 'feel a sort of half regret that I had ever left my former situation [as a janitor]' (*ibid.*, p. 36). It is unknown whether his health issues might have affected any inclination to undertake fieldwork. He had a 'horror of rain' but this did not prevent his making geological excursions when living in Glasgow at least (Irons, 1896, pp. 148, 155).

Croll's perceived money problems also run through his life story. His salary levels (Edwards and Robinson, 2021, their Table 2) show a progression, culminating in one of £350 *per annum* at the Geological Survey when the average salary for an adult male clerk in the UK during the 1880s was in the order of £50 *per annum* (Rosen, 2014). His resignation from the Survey meant that for the rest of his life he was adversely affected by the fight to obtain a just pension. His income was now reduced to £75 16s 8d along with a £40 *per annum* insurance annuity he had settled upon his wife. With

Archibald Geikie at the helm, the Treasury was petitioned in 1881 and 1883 on Croll's behalf, with the second signed by 153 individuals, who, from overlapping categories, included five peers, 13 knights, 35 Members of Parliament, 12 Chancellors, Vice-Chancellors or Principals of universities, 74 professors, 85 and 30 Fellows of the Royal Societies of London and Edinburgh, respectively, and 12 Presidents or Vice-Presidents of both national academies and other major learned societies,⁷ demonstrating further evidence of Croll's renown, connectedness and the esteem in which he was held. Croll was granted nothing, but various monies were forthcoming. Awards were received from the Geological and Royal Societies and an application to the Royal Literary Fund in 1885,⁸ with Archibald Geikie as one of its officers, resulted in the award of £100.

After a bewildering number of temporary homes stretching from Elgin in northeast Scotland to Dawlish in southwest England (Edwards and Robinson, 2021), James Croll retired to Perth in 1886 with financial assistance from friends, where he was 'fortunate in obtaining a lease of a comfortable house in the suburbs of the city' (Irons, 1896, p. 430) and where he died of a possible stroke in 1890, shortly before his 70th birthday. He is buried in Cargill churchyard, Perthshire.

Controversies

In spite of the accolades which came Croll's way, his published research did not always find favour. The pages of the *Philosophical Magazine* and *Nature* especially are studded with critical commentaries on the subjects of astronomy, climate change and oceanography. His biographer noted of Croll that 'though one of the most modest of men, he was a keen controversialist' (Irons 1896, p. 518). Two instances of his disputatiousness are presented here.

Newcomb, temperature and orbital dynamics

The more measured of his exchanges was with another autodidact, the Canadian-American astronomer and mathematician, Simon Newcomb (1835–1909). In his long review of *Climate and Time*, Newcomb (1876, p. 276) declaimed:

the weakness which everywhere marks Mr. Croll's reasoning on the subject of temperature. With all the care and study he has devoted to the subject, we are entirely unable to reconcile his views with the known laws of heat.

– and concerning glacial epochs (*ibid.*, pp. 270–273):

We may now pass to the consideration of the author's views of the cause of the Glacial epoch, or of glacial epochs in general, as, according to his view, there must have been several of them ... This computation we regard as entirely untrustworthy, being founded on purely hypothetical laws with purely hypothetical data ... We cannot therefore regard Mr. Croll's theory of a connection between the form and position of the

⁷Based on the data from the memorial itself (Irons (1896), pp. 544–548); other sources include Waterston and Macmillan Shearer (2006a, b). Most individuals are included within more than one of the assessed categories – e.g. they may be an FRS, an FRSE and a professor.

⁸British Library, Royal Literary Fund, Dr James Croll, 1885, Loan 96 RLF 1/2220.

earth's orbit and the Glacial epoch as having any reasonable show of foundation.

It took Croll seven years before he responded to Newcomb, and he did so relatively emolliently (Croll, 1883a, pp. 241, 243):

Considering the newness of the subject, and the complex nature of many of these combinations of physical agencies [orbital factors], it would not be surprising if some of the original deductions in regard to them proved erroneous ... Some of his objections, however, as will be seen, are based upon a misapprehension of my reasoning ... Surely Professor Newcomb must have forgotten all about the researches of Pouillet and Herschel into what has been termed the "Temperature of Space"...

There are rejoinders from both Newcomb and Croll to the foregoing. Newcomb (1884, pp. 142–143, 145) recorded:

The pleasure and interest with which I have read Mr. Croll's paper induce me to reply to it, notwithstanding a want of confidence on my part in the value of anything short of a purely mathematical investigation of the subject ... What we are concerned with is the inference that at some former epoch in geological history the mean temperature of the northern hemisphere was much lower than it is now. Assuming this as the basis of discussion, the question is what was the cause of this "glacial epoch"? ... [There is] a lack of quantitative precision in his language ... he most uses [terms] such as "great," "very great," "small," "comparatively small"....

[Regarding ocean and land temperature differentials] Mr. Croll substitutes a sound reason for this utterly bad one, but still seems inclined to hold on to the latter...

Croll's 'rejoinder' to the 'rejoinder' is one of exasperation (Croll, 1884a, pp. 275–276, 280):

I regret that I must repeat what I said about his Review, viz. that nearly all his objections are based on strange, and to me unaccountable, misapprehensions of my reasoning and of the views which I actually hold. I have no desire to continue this controversy ... Of course I fully concur in Professor Newcomb's opening remarks as to the desirability of "a purely mathematical investigation of the subject." Such an investigation, however, is, I think, impossible at present. In a question so complex and difficult as that of the cause of the Glacial Epoch, depending as it does on the consideration of so many different elements, some of which are but little understood, logical analysis rather than mathematics will require to be our instrument in the mean time ... Although my arguments are logical, few writers, I venture to say, have done more than myself to

introduce definite quantitative exactness into the questions I have discussed...

[Regarding heating] All this is so well known to every student of thermodynamics ... that I can hardly think Prof. Newcomb, on reflection, will dispute its accuracy.

Carpenter, winds and ocean currents

The most vitriolic exchanges – including responses publicly, privately and anonymously on Croll's behalf – were on oceanographic topics with William Benjamin Carpenter (1813–1885), Professor of Physiology at the Royal Institution, marine zoologist, and subsequently Registrar of University College London. Carpenter (1875a) had been able to draw upon the results of the HMS *Challenger* expedition (1872–1876; Thomson, 1878) and maintained that ocean currents were driven by differences in specific gravity and seawater density, with a general movement of seawater from the equator to the poles, whereas Croll suggested that they were driven mainly by winds as part of global atmospheric circulation (cf. Deacon, 1997; Mills, 2009; Dawson, 2021). This may have been 'a slightly irrational, noisy, dispute that is typical of sciences with insufficient data' (Wunsch and Ferrari 2018, p. 7.7), but it certainly enflamed opinions and Croll alone was to devote almost half of *Climate and Time* (Croll, 1875a) to aspects of ocean circulation.

What turned out to be an acrimonious debate, for Carpenter at least, may have begun when Croll (1870b, p. 233) took aim at the theory of the American oceanographer and meteorologist Matthew Fontaine Maury (1806–1873) as endorsed by Carpenter:

The latter theory [specific gravity] appears at present to be the more prevalent of the two, although, perhaps, not so among scientific men. It is difficult to conceive how a theory so manifestly erroneous should have gained such general acceptance.

– and like a dog gnawing at a bone, this was followed up with a sequence of substantial articles which further dissected Carpenter's arguments (Croll, 1871, 1874a, b). An incensed Carpenter (1874, p. 62) was to say:

MR. CROLL will doubtless be of opinion that as my "theories" show such an utter ignorance of "even the elements of physics and mechanics," I can employ my time much better in acquiring some knowledge of those sciences, than in continuing to discuss the subject with him...

It suited Mr. Croll's purpose, however, with these observations before him, completely to ignore them, and to state as fact what is the precise contrary of facts...

I have nowhere said that no eminent physicist shares Mr. Croll's objections; though I have not myself met with such a one...

I regret to have been forced, by the personal attacks in which Mr. Croll has latterly thought fit to indulge, thus to retort upon him. Henceforth I shall not consider myself called upon to take any notice of assertions and arguments which I do not find to exert the least influence on the opinions of the eminent scientific men with whom it is my privilege to associate.

This drew an anonymous attempt at pro-Croll mediation from, presumably, a Fellow of the Royal Society of London (F. R. S., 1874, pp. 83–84):

IN the interests of Science, of scientific discussions, and of scientific men let me be allowed to protest very earnestly against the manner in which Dr. Carpenter has thought fit to reply in your columns to the defence which Mr. Croll made against the representation of his views...

Mr. Croll, discarding unimportant details, asked attention to one or two cardinal "misapprehensions" ... But the Doctor, instead of plainly grappling with these ... runs off to call attention to a footnote of another paper of Mr. Croll's...

Now I strongly object to have dust thrown in my eyes in this way ... the discovery of anything "personal" in Mr. Croll's writings would be as great a find as the true theory of oceanic circulation.

The exchanges between Croll and Carpenter saw other interventions (e.g. Prestwich, 1871; Ferrel, 1872a, b; Airy, 1872–73). Archived letters are supportive of Croll with one suggesting that Carpenter 'may be at home in Foraminifera but in physics he is certainly as much at sea as if he were on The Challenger ... [he] has shuffled out of the matter under a cloud of irrelevant nonsense'.⁹ Another felt that Carpenter's work 'was made the more plausible through arguing upon false premises' and 'misrepresentation'.¹⁰ Events did not come closer to resolution until after the appearance of some of the data from the *Challenger* expedition that enabled Croll to produce his 'crucial-test argument' (Croll, 1875b, c, d), against which Carpenter seemed to flounder (cf. Carpenter, 1874, 1875b). Croll (1875e, p. 474) suggested that an implication of Carpenter's gravitation theory was untenable, one reason being that water could not 'flow up-hill' and Carpenter's own data showed that the North Atlantic at latitude 38° is above the level of the equator as a result of thermal expansion.

An anonymous reviewer of *Climate and Time* was in no doubt about the relative qualities of each protagonist (Anon., 1875, p. 323):

The manner in which Mr. Croll meets and combats Dr. Carpenter's theory of oceanic circulation is very characteristic of the unwearied patience, acuteness, and courage of his investigations. It is not our purpose

here to express any opinion on this unfinished controversy, further than to say that Mr. Croll follows Dr. Carpenter into every one of his positions with a resolution and tenacity of purpose which, were it not so really calm and passionless, might almost be looked on as cruel and unmerciful ... This he does not do with the intention of thrice slaying the slain, but simply because he has in an eminent degree the faculty of examining a problem from many sides; and he is concerned, not for dialectic triumphs, but for the presentation of truth in its entirety.¹¹

Practical glacial geology, a transactional involvement

Having observed that geology was a science 'for which I had no relish' Croll (1887, p. 14), he reprised his comment with added qualification (*ibid.*, p. 35):

I need hardly add that my duties as resident geologist really did not require much acquaintance with the science of geology. This relieved my mind from having to study a science for which I had no great liking, and thus allowed me to devote my whole leisure hours to those physical questions in which I was engaged. There was, however, one department of geological inquiry with which the physical questions, in which I was then engaged, required that I should be acquainted, namely, surface geology, or drift in its bearings on Glacial and Interglacial periods.

His biographer echoed the fact of Croll's frequent excursions while in Glasgow and the resultant 'writing on so abstruse a subject as Glacial Geology' (Irons, 1896, p. 148); 'whenever he had a holiday, it was invariably employed in visiting the scene of some geological formation ... Thus, in August 1868 ... [he] employed much of his leisure time in tracing the trough in the neighbourhood, and in hunting up erratic boulders in the fields thereabouts' (*ibid.*, p.195).

Rose (2021) has explored Croll's familiarity with glacial features. He suggested that Croll benefited from the existence of a 'Glasgow School' of glacial geologists (cf. Geikie, 1909; Braithwaite, 2011). Many of them seem unsung at the present day (e.g. James Smith, David Robertson, Henry Crosskey, Dugald Bell and Croll's later colleagues in the Geological Survey, James Bennie and Robert Jack), but their work inspired

¹¹Almost a century and a half later, a theological insight for the dispute between Croll and Carpenter has been advanced. Diarmid Finnegan (2012, 2021) outlines how Carpenter's religious beliefs emphasised actions of God as observable but not necessarily fathomable by empirical, inductive study. This was in opposition to Croll's belief in the existence of physical principles, albeit set in train by divine action, and capable of being interpreted by intellectual process. Carpenter saw the ways of God and nature as inscrutable, whereas Croll disagreed – the human mind was capable of discovering divine reasoning because nature was an orderly expression of a supreme intellect. Croll's complaint against Carpenter was the latter's reliance on a hypothetical cause rather than to known physical principles. Even if it is accepted that 'the debate was about more than science. A metaphysical dispute simmered beneath the surface' (Finnegan, 2012, p. 76), it is difficult to see that as driving the sustained effort that clearly went into the argument. For Croll at least, the metaphysics are indistinguishable from the science, while Carpenter was motivated by adherence to conventional beliefs concerning the movement of water between the equator and the poles.

⁹British Library, London, Add MS 41077, ff. 76, 77. 18 March 1874, Ely, from Sydney Barber Josiah Skerchly.

¹⁰British Library, London, Add MS 41077, ff. 78, 79. 12 August 1874, Tunbridge Wells, from Vice-Admiral Thomas Abel Brimage Spratt.

Archibald Geikie (1863) who was to facilitate Croll's move to Edinburgh. Irons (1896, p. 153) reported that Croll 'visited and inspected all the glens, river banks, and seashores in the neighbourhood of Glasgow, making careful notes of what he observed'.

This did not, though, translate directly into much published output. If the data in Table 2 are filtered further to select specific Scottish fieldwork with which he was involved, and which resulted in a publication, then it may embrace little more than a single paper which appeared after his arrival in Edinburgh (Croll, 1870c). The paper on buried river channels beneath drift between the Firths of Forth and Clyde drew attention in its first paragraph to 'the great defect' in short field sections. He later outlined the superior records from bore holes and sections in mine shafts which furnish more complete sequences, and this clearly enabled him to disclose his main interest (*ibid.*, p. 331–332):

[Of] '250 bores ... 25 have two boulder-clays ... 1 has no fewer than six separate masses of boulder-clay, with stratified beds of sand and gravel between; 16 have two or three separate boulder-clays, differing altogether in colour and hardness, without any stratified beds between ... 75 of them representing a condition of things wholly different from that exhibited to the geologist in ordinary sections. These bores bear testimony to the conclusion that the glacial epoch consisted of a succession of cold and warm periods, and not of one continuous and unbroken period of ice, as was at one time generally supposed.

His next sentence – 'The full details of the character of the deposits passed through by these bores, and their bearing on the history of the glacial epoch, have been given by Mr James Bennie' (*ibid.*, p. 332; cf. Bennie, 1868) – may reflect a tedium with the need to provide a detailed description of empirical data as opposed to theoretical concerns. Likewise, Croll notified James Murdoch Geikie (1839–1915), brother of Archibald, of a supposed interglacial peat sandwiched by tills, at Hailes Quarry, Edinburgh, which Geikie (1881, pp. 256–261) described after a visit in 1878.

Other than for information on the Pentland Hills contained in a postscript, a two-part paper on the boulder clay of Caithness (Croll, 1870d, e) does not feature field results from Croll. It is based especially on published and unpublished research by Thomas Francis Jamieson (1829–1913) and Charles William Peach (1800–1886). Its tone is not that of a man uncertain of his views (Croll 1870d, p. 211):

I have always felt convinced that Mr. Jamieson had not hit upon the true explanation of the phenomena ... It is physically impossible that any deposit formed by icebergs could be wholly unstratified ... The notion that unstratified Boulder-clay could be formed by deposits from floating ice, is not only erroneous, but is also positively pernicious, for it tends to lead those who entertain it astray in regard to the whole question of the origin of drift ... It is also physically impossible that ice-markings, such as those everywhere found on the rocky face of the district, and on the imbedded pebbles and shells found in the clay, could have been

effected by any other agency than that of land-ice. I need not here enter into any discussion on this point. This has been done at considerable length on a former occasion [Croll 1868c] ... if it can be shown that all the facts can be accounted for in the most natural manner by the theory of land-ice, no one will seek to contend for the floating-ice theory...

In the boulder clay papers, Croll's observations, drawing partly on C.W. Peach, emphasised that Caithness was glaciated by land ice from Scotland moving across the bed of the North Sea which was deflected back to shore by Scandinavian ice. This was arguably a significant contribution to Quaternary science in two respects: firstly, in terms of ice-sheet movements and the presence of blocking countervailing (Scandinavian) ice (as also applied to Shetland and Orkney); and secondly, in refutation of the glacial submergence theory and that the presence of (ice-worn) shells in till were a product of marine submergence. Subsequent research has unsurprisingly added detail to ice-flow patterns, the variable locations of the Fennoscandian Ice Sheet, and posited the existence of an independent ice cap on Shetland (Ballantyne and Small, 2019; Hall et al., 2019; Merritt et al., 2019), but this does not negate the far-reaching insights emanating from Croll.¹²

The quotation at the start of this section suggests that Croll had a transactional relationship with glacial geology in that it aided his engagement with 'physical questions'. It seems likely that he felt that instances such as that of the boreholes from the buried river channels or the growing number of reported inorganic/organic sequences in sections were best interpreted as providing a test of his theory (cf. Rose, 2021, p. 269–270) – orbital dynamics worked through changing insolation as a driver for the occurrence of multiple glacial and interglacial cycles. There is no evidence that Croll considered them to indicate possible alternating climatic fluctuations reflecting local ice advances, with tills relating to ice-marginal fluctuations and having no real bearing on his grand model with its much longer timescales. It is quite clear from his commentary on the ideas of Alfred Russel Wallace (1823–1913; Croll, 1884b, pp. 370–373), that Croll related the interglacial deposits of Scotland and the rest of Europe to 'the Physical theory of the cause of the Glacial Epoch' (*ibid.*, p. 373). This might also be construed from a letter to Wallace dated 24 July 1880 (in Irons, 1896, pp. 359–360):

The amount of evidence uncollected, which lies scattered over the various journals and papers of America and the Continent, is perfectly astonishing. This will be brought out very strongly by Dr. James Geikie in his forthcoming work on Prehistoric Man in Europe. It is, I think, now beyond question that the Glacial epoch consisted of a succession of cold and warm periods, which must be accounted for in any

¹²In their publications on the glaciation of Shetland and Orkney, Benjamin Neeve Peach (1842–1926), the son of Charles W. Peach, and John Horne, credited Croll as the first to suggest the presence of an ice sheet (which he initially surmised as part of a polar ice cap) in the North Sea (Peach and Horne, 1879, 1880), noting that Croll had suggested this in a paper published in *The Reader* (Croll, 1865; though the idea there is not stated overtly). Croll (1870d, p. 212) said that he was informed around 1868 of C.W. Peach's view that land ice from the southeast (presumably from the Cairngorms) had moved from the Moray Firth across Caithness. Croll, however, considered that such a theory is only 'part of the truth' as ice would not escape the Moray Firth, but would take the line of least resistance and move into the North Sea from which Scandinavian ice would then deflect it towards Caithness.

theory of geological climate. In fact, these periods are the general test of theories of climate ... They have all along convinced me that the only possible way of explaining them is by the hypothesis that these alternations were due to the precession of the equinoxes at the time of high eccentricity.

Using Croll: James Geikie's 'pretence of induction'

Croll's distrust of shallow terrestrial deposits, at least in so far as they can contribute reliably to the testing of theory in climatically related geology, was placed in another perspective concerning James Geikie, Croll's Edinburgh work colleague. Hamlin (1982) examined James Geikie's seven-paper exposition 'On changes of climate during the Glacial epoch' which appeared in the *Geological Magazine* for 1871 and 1872. These papers formed the basis of *The Great Ice Age* (Geikie, 1874). In them, Geikie advanced what was then a modern view of the Ice Age characterised by alternating cold (glacial) and warm (interglacial) climates with water-deposited clays, sands and gravels intercalated with glacial till, and featuring the associated phenomena such as moraines, erratics, striae and shell beds for which correlations may be attempted. Hamlin showed that Geikie had an inherent adherence to Croll's theory, although 'Geikie's conclusions about the length, mildness, and frequency of interglacial periods went beyond what inductive geology could support ... and his correlation of interglacial deposits rested on the assumption of climatic universality, an assumption with no basis in the evidence available to him ... but an assumption which formed a central part of Croll's climatology' (Hamlin, 1982, pp. 566–567).

Geikie was treading tactfully in an era when acceptance of land-based glaciation, as opposed to the iceberg/drift theories compatible with catastrophism/diluvialism and Biblical writ, was not universal (*cf.* Belt, 1874; Chorley et al., 1964; Davies, 1968; Boylan, 1998; Oldroyd, 1999; Ehlers et al., 2015). Indeed, the major debate in Britain between those advocating for land ice, with William Buckland (1784–1856), Louis Agassiz (1807–1873) and, temporarily, Charles Lyell (1797–1875) to the fore, and opponents including especially Sir Roderick Impey Murchison (1792–1871) and, initially, William Hopkins (1793–1866) ranged against them, simmered for decades beyond the 1870s (*cf.* Bonney, 1911; the topic is summarised engagingly by Woodward, 2014).¹³ Croll was somewhat aloof from this, having long embraced Archibald Geikie's notions of glacial theory (Geikie, 1863; Croll, 1868c; Rose, 2021).

The inference that Croll's theory was 'the key assumption which enabled [James] Geikie to make sense of Ice-Age deposits, rather than a conclusion obtained through intensive study of Pleistocene strata' (Hamlin, 1982, p. 566) was part of Geikie's 'pretence of induction' (*ibid.*, p. 577). It is only in the final two pages of the seventh paper that Geikie (1872, p. 264) discussed the importance of Croll's theory of climate changes:

Hitherto no reference has been made in these papers to Mr. Croll's theory of the physical cause of changes of climate during geological epochs. That theory for the first time rendered possible the reconciliation of apparently contradictory facts. Phenomena which had refused to be explained by any number of ingenious hypotheses suddenly seemed to yield their secret, and the great "Age of Ice" appeared all at once in a new light.

Geikie was not intending to slight his work colleague by an afterthought – to Hamlin, the organisation of Geikie's papers was intentional as to do otherwise would have invited scepticism amongst 'numerous geologists for whom any conclusions about Earth history not clearly the product of traditional geological endeavour were automatically suspect' (Hamlin, 1982, p. 588). Croll himself was no stranger to such disbelief or distrust and would have understood this expedient; after all, 'He was rarely heard, even by his most intimate friends, to speak on religious topics. When, however, theological subjects were discussed in his presence, he freely granted to earnest thinkers the liberty of thought which he claimed for himself' (Irons, 1896, p. 497).

The last paper that wasn't, and marine coring

In the final paragraph of a paper on arctic interglacials (Croll, 1885b, p. 42), we read:

NOTE.—This will probably be my last paper on questions relating to geological climate. There are many points I should have wished to consider more fully, but advancing years and declining health have rendered it necessary for me to abandon the subject altogether in order to be able to finish some work, in a wholly different field of inquiry, which has been laid aside for upwards of a quarter of a century.

Except it was not so. Subsequent years saw the appearance of climate-related contributions on subaerial denudation and glaciation (Croll, 1889a, b), including a one-sentence note in *Nature* in the year of his death (Croll, 1890; Fig. 5); and these were in addition to his books on climate and cosmology (Croll, 1885a) and stellar evolution and geological time (Croll, 1889c).

The final geological item published by Croll (1890; Fig. 5) had an attenuated resonance with earlier comments (Croll, 1868a, p. 376). The former noted a process of erosion and its oceanic deposition; the latter suggested the same process for a different period when he asked 'May not the greater portion of the Tertiary deposits be still under the sea-bottom? And if this be the case, it may yet be found at some day in the distant future, when these deposits are elevated into dry land ...'. It is in the pages of *Climate and Time* that a more developed concept is outlined (Croll, 1875a, p. 287):

In regard to former glacial epochs, however, ice-marked rocks, scratched stones, moraines, till, &c., no longer exist; the land-surfaces of those old times have been utterly swept away. The only evidence, therefore, of such ancient glacial epochs, that we can hope to

¹³This was not, of course, a solely British process. For instance, the Dano-Norwegian geologist Jens Esmark had written of the greater past extent of Norwegian glacier ice, and the zoologist Louis Agassiz had benefited from the earlier glacial researches of fellow Swiss engineer Ignace Venetz (1788–1859), mountain guide Jean-Pierre Perraudin (1767–1858) and the German-Swiss engineer and geologist Jean de Charpentier (1786–1855). In the USA, both pre- and following Agassiz, theologian and geologist Edward Hitchcock (1793–1864) and geologists Timothy Abbott Conrad (1803–1877) and James Dwight Dana (1813–1895) embraced glacial rather than diluvial explanations for landform history.

Former Glacial Periods.

I HAVE long felt convinced that geologists are being misled in reference to former glacial epochs by failing to give due thought to a consideration referred to on former occasions,¹ viz. that when the present surface of the globe has been disintegrated, washed into the sea, and transformed into rock, there will undoubtedly then be about as little evidence that there had been a glacial epoch during post-Tertiary times as there is at present that there was one during Miocene, Eocene, Permian, and other periods.

JAMES CROLL.

Perth, March 6.

Figure 5. The one-sentence note in *Nature* (Croll, 1890) – his last geological offering, published 13 March 1890. The superscript footnote 1 reads ‘Quart. Journ. Geol. Soc. for May 1889; “Climate and Time,” p. 266.’

detect, must be sought for in the deposits that were laid down upon the sea-bottom; where also we may expect to find traces of the warm periods that alternated during such epochs with glacial conditions.

This is expanded upon over the following two pages and Imbrie and Imbrie (1979, p. 123) regarded this as showing that Croll ‘had anticipated the day when geologists would be able to obtain a more complete record of the ice-age sequence by delving into the sea bottom’. It might be a bit of an inferential jump to infer that Croll was predicting deep-sea coring and palaeoceanography (cf. Tzedakis and Wolff, 2021, p. 3), but he would likely have reached that position had he been alive to see even the early developments and results of coring technology in the following century.

Astronomical approach to climate change: Croll and a landmark paper

Croll’s writings on an astronomical approach to climate change were not produced in intellectual isolation. The potential relationship between the orbital dynamics of the Earth and climate has been long recognised, and Hilgen (2010), Berger (2012) and Paillard (2015a), for example, instance Jens Esmark (1763–1839), Alexander von Humboldt (1769–1859), John Frederick William Herschel (1792–1871), Joseph Alphonse Adhémar (1797–1862) and Charles Lyell, amongst others, in the period leading up to Croll’s research. Unsurprisingly, there were also antecedent contributions relevant to celestial mechanics, if not climate change (Longair, 2021). The French mathematician Adhémar (1842) is credited with being ‘the first to present a full astronomical theory of the ice ages’ (Hilgen, 2010, p. 66) having combined the Ice Age theory of Louis Agassiz (1840) with orbital dynamics and climate suggestions of Lyell (1830–33) and Herschel (1832).

Croll recognised that others had accomplished much within the field. His seminal 1864 paper cites in excess of 20 other names (including Humboldt, Agassiz, Lyell and Herschel). He also considered the orbital variations formulae of Urbain Jean Joseph Le Verrier (1811–1877), which were to enable Croll to devise retrospective (3 million years) and prospective (1 million years) chronologies for eccentricity (Croll, 1866, 1867a, 1875a); the Frenchman himself was little interested in the astronomical theory of palaeoclimates (Berger, 2012). In *Climate and Time*, Croll devoted an 18-page appendix to ‘Opinions expressed previous to 1864 regarding the influence of the

eccentricity of the earth’s orbit on climate’ by 14 individuals (one third of the space is devoted to John Herschel). The biggest omission in the orbital dynamics papers is Adhémar, though he appeared in a paper on heat radiation differentials between the southern and northern hemispheres (Croll, 1869) and he was to be considered, somewhat dismissively, in a little over two pages as the final person in the appendix to *Climate and Time* (Croll, 1875a, pp. 542–544).

A landmark paper

Although his summative book of 1875 is most cited in respect of the astronomical theory of ice ages, the recognised starting point is his 1864 paper (Croll, 1864b; Fig. 6). Its genesis was described in the *Autobiographical Sketch* (Croll, 1887, pp. 32–33):

... the question of the cause of the Glacial epoch was being discussed with interest among geologists. In the spring of 1864 I turned my attention to this subject; and, without knowing at the time what Herschel and Lyell had written on the matter, it occurred to me that the change in the eccentricity of the earth’s orbit might probably be the real cause. I accordingly drew up a paper on the subject, which was published in the Philosophical Magazine for August 1864. The paper excited a considerable amount of attention, and I was repeatedly advised to go more fully into the subject; and, as the path appeared to me a new and interesting one, I resolved to follow it out. But little did I suspect, at the time when I made this resolution, that it would become a path so entangled that fully twenty years would elapse before I could get out of it.

A year later, his future employer observed prophetically (albeit in a footnote; Geikie, 1865, p. 166):

The true explanation of this confessedly difficult subject is, I believe, that given recently by Mr. Croll, who accounts for the recurrence of cold and warm periods in the geological history of the globe by changes in the eccentricity of the earth’s orbit. His paper ... is one of the most important contributions which have been made to geology for many years. Among its fruitful results will probably be the key to the value of geological time.

Given its iconic status as a landmark statement in science, the paper is surprisingly short on detail, especially numerical, and long on generalised prose, though there is no disguising the breadth and insights on display. The first nine pages examined earlier work (e.g. by Herschel, Frankland, Poisson and Lyell) and asked critical questions concerning the varying hot and cold natures of geological periods since the Palaeozoic. Biotic evidence was combined with critical discussions of the heat of space, the Earth’s internal heat, land–sea movements and interactions, and ocean currents (especially the Gulf Stream) and winds. The kernel of the paper is not reached until half-way through its 17 pages (Croll, 1864b, p. 129):

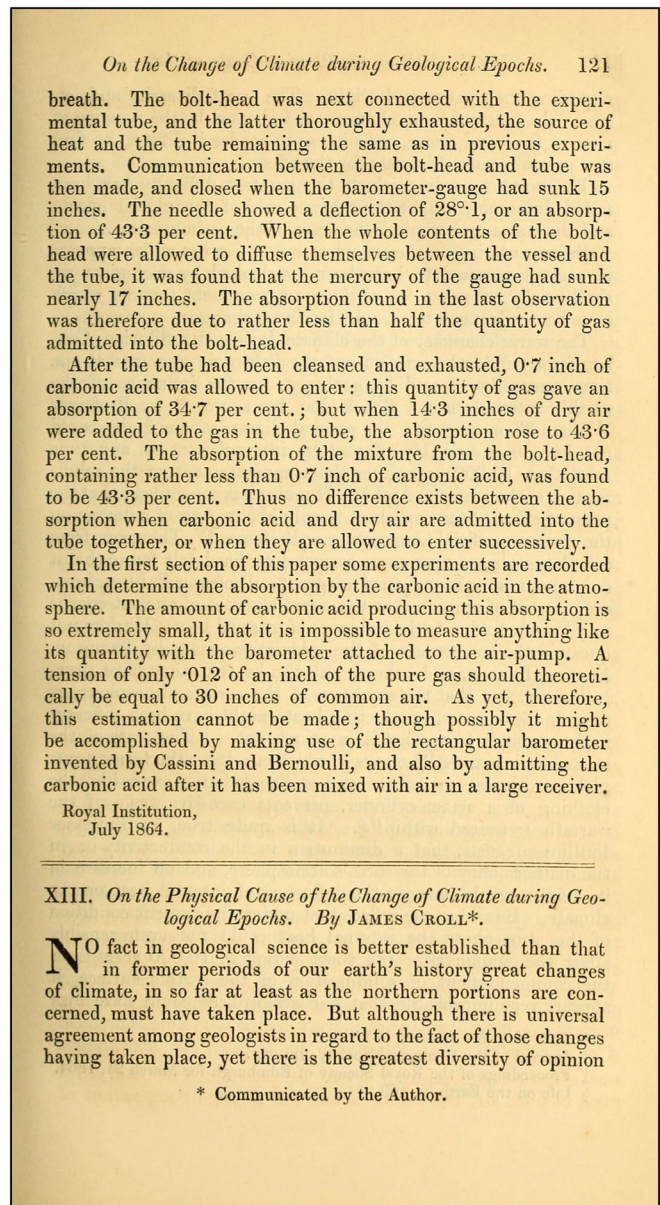
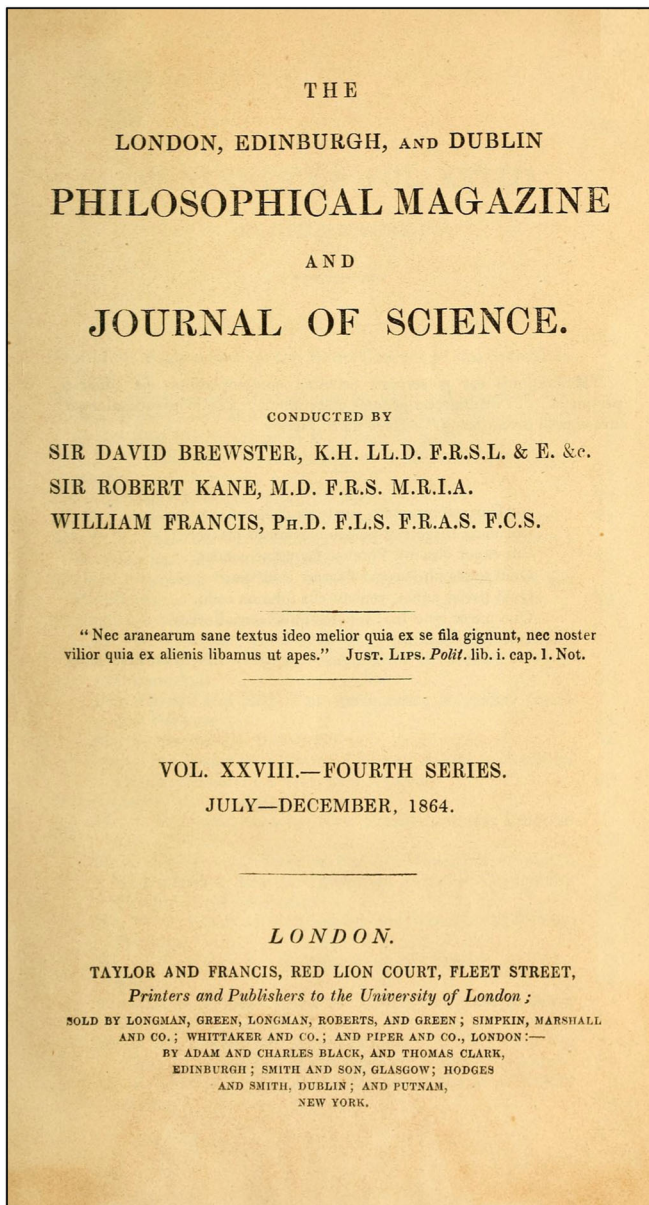


Figure 6. Cover of the *Philosophical Magazine* (left) in which Croll's paper on climate (from page 121, right) appeared.

... all these hypotheses which have come under our consideration ... [are] irreconcilable with the idea of a regular succession of colder and warmer cycles.

The recurrence of colder and warmer periods evidently points to some great, fixed, and continuously operating cosmical law.

We have already referred to the hypotheses of our system passing through colder and hotter parts of space, and of the shifting of the earth's axis of rotation, and have shown that they receive no support whatever from the known facts and principles of physical science. The true cosmical cause must be sought for in the relations of our earth to the sun.

There are two causes affecting the position of the earth in relation to the sun, which must, to a very large

extent, influence the earth's climate; viz., the precession of the equinoxes and the change in the eccentricity of the earth's orbit. If we duly examine the combined influence of these two causes, we shall find that the northern and southern portions of the globe are subject to an excessively slow secular change of climate, consisting in a slow periodic change of alternate warmer and colder cycles.

– along with (p. 133) a further physical attribute:

Under a cloudless sky, the direct rays of the summer-sun would, in our latitude, be more than sufficient to remove the winter's accumulation of ice and snow. But if from thick fogs or an overcast sky the direct rays of the sun were prevented from penetrating to the earth, the heat of summer would not in such a case be sufficient to remove the snow and ice; and the formation of glaciers would be the inevitable result.

It should be noted that two key parts of what are recognised as part of Croll's 'system', axis obliquity (tilt) and albedo feedbacks, make their first appearance in other papers (*viz.* Croll (1867b, c) and Croll (1870a), respectively) though not, as often cited, in the 1864 paper or in *Climate and Time*. Albedo is introduced when Croll tackles the issue of ocean currents in relation to his theory of climate (*ibid.*, p. 184) – 'Another cause of the cooling effect is that the rays which fall on snow and ice are to a considerable extent reflected back into space.' The significance and complexity of feedbacks are brought out in Croll (1875a, pp. 14, 68–69) as summarised in Irons (1896, p. 228) – 'The cause of secular changes of climate is the deflection of ocean currents, owing to the physical consequences of a high degree of eccentricity of the earth's orbit' – and by Horne (1892, p. 174): 'To Dr Croll belongs the rare merit of showing that, though glacial cycles may not arise *directly* from cosmical causes, they may do so *indirectly*.'

Croll clarified and refined the ideas within the paper over the next two decades (e.g. Croll, 1866, 1867a, b, 1875a, 1878, 1884b, 1885a). Many, like Darwin, John Tyndall (1820–1893) and the Geikie brothers, embraced the theory, whereas dissenting views are not difficult to find, ranging from mild

annotations (Fig. 7) on an offprint of Croll (1878) by Celtic folklorist, geologist and meteorologist John Francis Campbell (inventor of the Campbell–Stokes sunshine recorder), to the less restrained from geologist Alexander Somervail (1877):

The interglacial periods being the necessary outcome or consequence of the astronomical theory, as elaborated by Dr Croll, the stratified deposits occurring in the till have been eagerly seized upon and compelled to do service in its behalf; so that we cannot escape the conviction that the whole reasoning moves in a most pernicious circle. (p. 94)

It is very evident that the astronomical theory, as elaborated at present by Dr Croll, involves so many difficulties as to completely destroy itself. (p. 97)

Hilgen (2010), Thompson (2021) and Tzedakis and Wolff (2021) provide informative summaries of the technical features associated with the development of Croll's astronomical theory of climate.

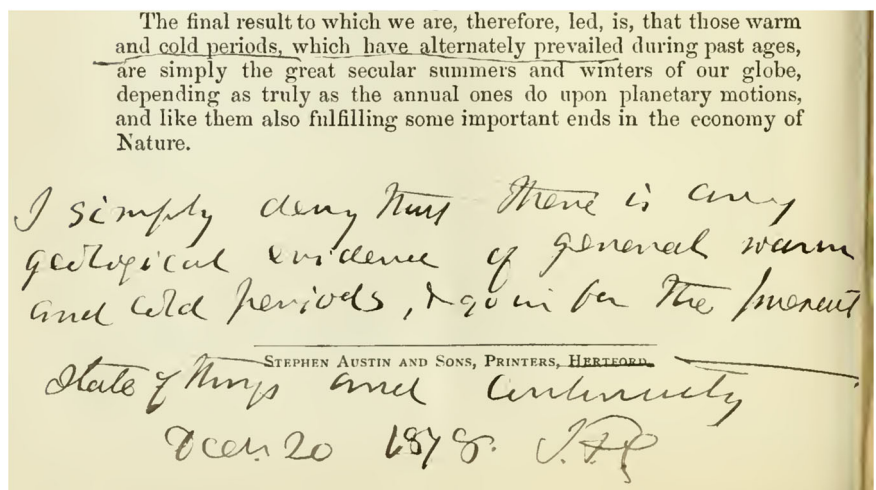
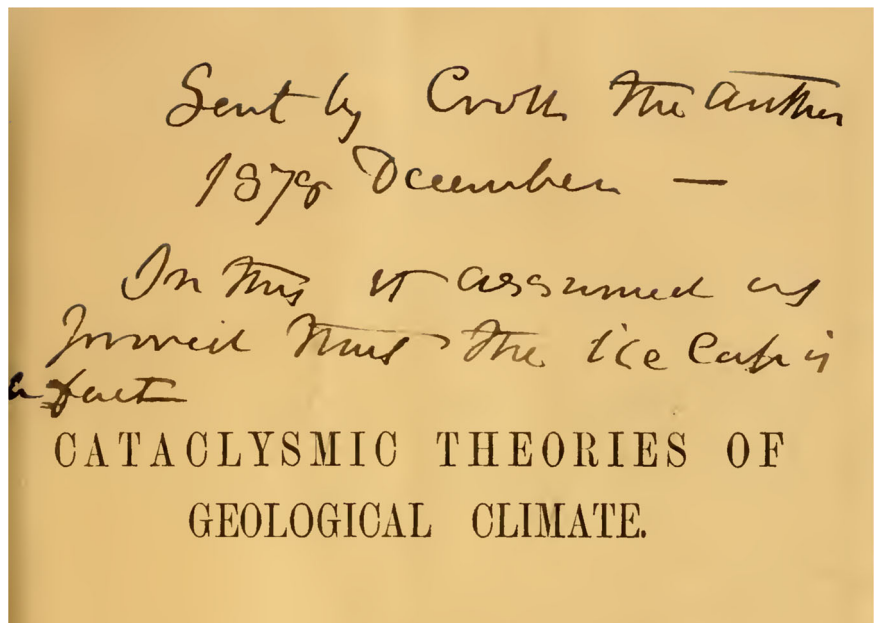


Figure 7. Offprint of Croll (1878) annotated by John Francis Campbell by whom it is dated to December 20th 1878 and initialled J.F.C. The annotations on the front cover (top) read 'In this is assumed as proved that the ice cap is a fact', and those on the final page (bottom) 'I simply deny that there is any geological evidence of general warm and cold periods, & go in for the present state of things and continuity'. (From the National Library of Scotland, J.F. Campbell Collection, MMSID: 9922989113804341).

The rise, fall and rise again of Milutin Milankovitch

By the time that Croll died in 1890, affection for him had not dimmed (A.G. 1890; J.G. 1890; Horne 1892), even amongst those who recognised his willingness to be a controversialist (Anon., 1890), but his scientific reputation had waned. This stemmed from a variety of factors, but three stand out (*cf.* Fleming, 2006): he had inferred incorrectly that glacial periods would alternate between the northern and southern hemispheres, as had Adhémar; the stratigraphic evidence was inconclusive or refuted (Petrović, 2012); and the timing of his events was simply not believed. With regard to the last of these, the final sentence of his 1864 paper was unfortunate: 'We may therefore safely conclude that it is considerably more than 100,000 years since the glacial epoch' (Croll, 1864b, p. 137). In North America particularly, apart from raising issues of stratigraphic evidence and doubts over hemispheric climatic synchronicity, it was felt from relative dating evidence that 'the Glacial period closed ... not more than 10,000, or at most 15,000 years ago ... instead of 150,000, or at the least 80,000 years, as the eccentricity hypothesis requires' (Dana, 1896, p. 978).

An astronomical hiatus was filled with geochemical theories for climate associated with CO₂ concentrations (Arrhenius, 1896; Chamberlin, 1897; Callendar, 1938; Fleming, 1998) and arguments concerning glaciations and greenhouse gases continue to arise (Paillard, 2015a, b; Bol'shakov and Kuzmin, 2015). Of critical importance was the revival of the astronomical dimension by a Serb, Milutin Milankovitch (Milanković/ć; 1879–1958), with encouragement from the Russo-German climatologist Wladimir Köppen (1846–1940) and his geophysicist son-in-law Alfred Lothar Wegener (1880–1930) (Köppen and Wegener, 1924). As a mathematical engineer with a lot of time on his hands (he was a prisoner of war during the Austro-Hungarian war), Milankovitch (1920, 1930, 1941) presented laboriously calculated insolation curves through time for differing latitudes on Earth (as well as for temperatures at the surfaces of Mercury, Venus, Mars and the Moon; Petrović, 2012).

Milankovitch considered Croll's theory to be the 'most remarkable' of the preceding ice age theories as it 'correctly recognizes the influence of the eccentricity of the Earth's orbit upon the duration of the astronomic seasons', but 'the influence of the variability of the obliquity upon the insolation is not sufficiently taken into account' (quoted in Fleming, 2021, p. 4). In contrast to Croll, Milankovitch's results were highly quantitative, rather than being a mix of description and basic mathematics and he was able to accommodate considerations of orbital dynamics more rigorously. He also maintained that a key element for ice age triggering was latitudinal insolation and cold summers, rather than cold winters and seasonal insolation of whole hemispheres (Petrović, 2012).

Like, Croll, however, Milankovitch's theory suffered neglect (Petrović and Marković, 2012; Fleming, 2021), especially after the radiocarbon-dating of glacially related deposits and the apparent failure to endorse the Serb's chronological predictions (Imbrie and Imbrie, 1979). Resurrection arrived in the form of deep-sea sediment cores, with their relatively stable depositional environments, and the determination of multiproxy stratigraphies for planktonic foraminifera, oxygen isotopes and a range of temporal measures (e.g. Emiliani 1955; Ericson and Wollin, 1956; Shackleton, 1967; Shackleton and Opdyke, 1973). These studies culminated in the 'pace-maker' paper by Hays et al. (1976) which revealed spectral

peaks at periods of 23 kyr (25% of the variance; *cf.* precession), 42 kyr (10% of the variance; *cf.* obliquity) and 100 kyr (50% of the variance; *cf.* eccentricity), allowing the conclusion that 'changes in the earth's orbital geometry are the fundamental cause of the succession of Quaternary ice ages' (*ibid.*, p. 1131).

Subsequent work has extended investigations to marine, terrestrial and ice core records and refinements continue to appear (e.g. Abe-Ouchi et al., 2013; Margari et al., 2014; Tzedakis et al., 2017; Liautaud et al., 2020; Westerhold et al., 2020). There is even a 'new theory' of astronomical climate change (Smulsky, 2016, 2020). Perspectives critical of the Milankovitch theory, including inconsistencies in applying its principles (e.g. Bol'shakov, 2003, 2008, 2017; Puetz et al., 2016; Connolly et al., 2021) and reputed failures to acknowledge Croll sufficiently (Bol'shakov and Kuzmin, 2015; and see below), are also to be found.

Croll–Milankovitch?

A champion of Croll has been Vyacheslav A. Bol'shakov, a mathematical physicist and geographer at Moscow State University (e.g. Bol'shakov, 2008, 2014, 2017; Bol'shakov and Kapitsa, 2010). He has commented quizzically (Bol'shakov, 2003, pp. 128–129):

It remains an enigma why, despite so many discrepancies between the Milankovitch theory and empirical evidence, it avoided being discarded, as the Croll theory did not (in due course and for similar reasons), and why its basic tenets were not even put to critical analysis.

Declarations for Croll within Bol'shakov and Kapitsa (2011), though with more space devoted to orbital theory and Milankovitch, met a response from Smul'skii (2013) which addressed their methodology and, briefly, gently commented upon the history ('From time to time, it is necessary to recall original ideas: which of them have been realised, and which were lost and should be reconsidered' (*ibid.* p.53)). In true controversialist fashion, Bol'shakov (2013, pp. 56, 58) produced 'An answer to I.I. Smul'skii's criticism':

Smul'skii's incorrect presentation of some of our conclusions, interpretations, and approaches to the solution of a number of problems discussed ... is especially regrettable. Such distortions may give rise to doubts that Smul'skii's goal in the discussion is search for truth...

Unfortunately, when it comes to criticism of these that are assumed to be universally recognized, one often faces a great number of their defenders, who, however, as my experience shows, often know next to nothing about the essence of the problem under discussion. The usual reaction to the axiomatic argument "the Milanković theory is invalid because it contradicts empirical data" is that it is recognized by the entire scientific world.

In his 'new theory', Smulsky (2016, pp. 1, 19) acknowledged those who 'fathered' the astronomical theory – Agassiz (1840), J. Adhémar (1842), J. Croll (1864b), R. Hargreaves (1896) – and whose work was 'completed' by Milankovitch (1930).

Others have been confident in promoting naming rights when citing primacy or significance:

- the ‘Croll-Milankovitch-Bacsák¹⁴ theory’ and ‘Croll-Milankovitch perturbation effects’ (Fairbridge, 1961, pp. 544, 560);
 - the ‘Croll-Milankovitch hypothesis’ (Goudie, 1983, p. 212);
 - ‘Croll-Milankovitch cycles’ or ‘forcing’ (Rogers, 1993, pp. 19, 21);
 - ‘Croll/Milankovitch’ ‘theory’, ‘insolation model’ or ‘insolation mechanism’ (Muller and MacDonald, 1997, pp. 215, 216, 218);
 - ‘Croll/Milankovitch orbital cycles’ and ‘Croll-Milankovitch warming’ (Sugden et al., 2011, p. 31);
 - ‘Croll-Milankovitch climate cycles’ (Gamble, 2021, p. 239).
- while Croll is absent in other formulations:
- ‘Milankovitch-Bacsák theory’ (Kriván, 1955; Szarka et al., 2021, p. 704);
 - ‘Milanković-Berger¹⁵ cycles’ (Petrović and Marković, 2012, p. 116).

A recent, admittedly brief, celebration of Milankovitch ignored Croll and all previous workers (Cvijanovic et al., 2020). In contrast, Bol’shakov et al. (2012, p. 202) had maintained that:

Croll was the first to consider the effect of positive feedback, which increased the effect of orbital variation of insolation and transformed that variation into global climate change, that is into glaciations and interglacial periods. That is the main achievement of his theory, and to our mind, is the most important discovery in paleoclimatology. Its consequences are not yet sufficiently recognised.

Final comments

Apart from the biographical material presented in this paper, the scientific work which fully entitles James Croll to be regarded as a Quaternary scientist has purposely been emphasised. Indeed, the James Croll Medal is the senior award of the UK Quaternary Research Association (QRA), which is testament to the high esteem in which he has come to be regarded.¹⁶ There has only been passing allusion to his earlier outputs on heat and electro-magnetism, and little more

¹⁴György Bacsák (1870–1970), Hungarian interpreter and developer of Milankovitch’s ideas (cf. Szarka et al., 2021).

¹⁵André Léon Georges Chevalier Berger (born 1942), palaeoclimatologist and emeritus professor at the Catholic University of Louvain, who has written extensively on orbital theories of climate change.

¹⁶The background and criteria for the award are to be found on the QRA’s website (<https://www.qra.org.uk/prizes/> (accessed 18 November 2021)): ‘This is the highest award of the QRA and is named in honour of James Croll (1821–1890). Croll is most closely associated with fundamental work on the astronomical theory of the ice ages, but he also made seminal contributions on the glacial geology of Scotland, on the mechanisms that drive ocean circulation and the impact of that circulation on recent climate, on tidal theory and the rotation of the Earth. These are all major issues that occupy Quaternary scientists to this day. Croll was effectively self-taught. His work and example demonstrate that any individuals from all backgrounds can rise to national eminence and generate science of lasting and major international impact, that it is not who you are or where you come from but what you do that is important. These are the qualities that the QRA seeks to celebrate in the award of the James Croll Medal. The Medal is therefore normally awarded to a member of the QRA who has not only made an outstanding contribution to the field of Quaternary science, but whose work has also had a significant international impact.’

on his religious philosophy – one of the ‘more noble and ennobling studies than science’ (Irons, 1896, p. 262). He considered his paper ‘Evolution by force impossible: a new argument against materialism’ (Croll, 1883b) to be ‘by far the best thing I have ever written’ (Irons, 1896, p. 368).

Intriguingly, given his breadth otherwise, there was a near complete absence of antiquarian comment. He was in contact with archaeologists (John Lubbock (1834–1913), John Evans (1823–1908), Joseph Prestwich (1812–1896) and Flinders Petrie (1853–1942)), his candidature for the Royal Society of London was supported by the first two of these, and in his lifetime his research was quoted in archaeological or antiquarian contexts by, for instance, Carter (1874), Plunkett (1875), Birks (1878), Lubbock (1882) and Spiers (1883). Tangentially, there is an account by fossil-collector James Bennie of a walk to Allander, Dunbartonshire, with Croll in 1867, when the cultural monuments and landscapes en route excited Bennie, whereas there is no indication that Croll was intent on anything other than examining putative drift deposits (Irons, 1896, pp. 161–164). There was also an exchange of letters with his Cambridgeshire friend the Reverend Osmond Fisher (1817–1914) in 1877, where Fisher discussed deposits containing ‘interglacial flint implements’ which had also been examined by James Geikie and Sydney Barber Josiah Skertchly (1850–1926). This undoubtedly referred to the Lower Palaeolithic artefacts in the Hoxnian (MIS 11) interglacial deposits at Beeches Pit, West Stow, Suffolk (Preece et al., 2006, 2007).¹⁷ Croll’s response concentrates on the deposits rather than the artefacts. He did observe (Croll, 1868a, pp. 381–382) that ‘one foot removed off the general level of the country since the creation of man [6000 years ago], according to Mosaic chronology, is certainly not a very great quantity’. He did not, of course, believe in that chronology.

Perhaps it was a case of being ‘not cosmopolitan’, ‘nor encyclopaedic’ as shown by the following glimpses of Croll from James Bennie (Irons, 1896, pp. 155–156:

As Mr. Croll had a horror of rain, and would not go out in it, I was frightened throughout the day by every dull blink that occurred ... I found Mr. Croll’s ‘crack’ good, quiet, undemonstrative, but full of pith and power. I cannot remember half of what he said, but the impression that remained was that he was a close observer and deep thinker on those objects he had seen or those subjects he had thought upon, but he was not cosmopolitan in the extent of objects nor encyclopaedic in the range of subjects, as, indeed, in this age, when knowledge fills the earth as the waters fill the sea...

¹⁷Skertchly published a section drawing of the brickpit, then still active, showing the location of the flint implement (Whitaker et al., 1891, Fig. 18). The main interest in this site for Croll, as surmised by Fisher, would likely have been the alleged occurrence of two tills, one below and the other above the level containing the undiagnostic ‘interglacial flint implements’. Fisher (Irons, 1896, pp. 322–323) was sceptical about the interpretation of the upper sediments as true till and writes to Croll that this was ‘what is called in your part of the world, not proven’. It is now known that the lower (and only) till at West Stow is Anglian (MIS 12), that the interglacial deposits are Hoxnian (MIS 11), that they contain *in situ* Lower Palaeolithic archaeology, including evidence of hearths (Preece et al., 2006), and that there is no upper till, as claimed by Skertchly. However, interestingly, although there is no upper till, there is faunal evidence (molluscs, ostracods and lemming) for a cold stage represented by sediments in the uppermost levels (Preece et al., 2007). I am grateful to Richard Preece for information on the site. There is no evidence that Croll visited the site when he stayed with Fisher in March 1882 (Appendix 1).

Croll may have been a self-declared, reluctant geologist, but this applied to his innate lack of interest in the subject and his view that processes of denudation, glaciation and the incomplete terrestrial record hobbled the testing of his cosmological ideas. It did not stop him citing findings from the discipline when it suited. James Geikie may have had the ability to provide the framework (plus the polish and the establishment credentials) that allowed ‘the birth of Quaternary Science’ (Rose, 2021, p. 13) – he also went on to become a founder of the Royal Scottish Geographical Society (Lochhead, 1981) – yet Geikie benefited from Croll’s intellectual agenda which embraced the likes of glacial–interglacial cycles and land–sea–atmospheric interactions in a whole-systems approach of cosmic proportions. As others have remarked in near unison (Bol’shakov et al., 2012; Sugden, 2014; Woodward, 2014; Dawson, 2021; Longair, 2021), Croll was a thinker far ahead of his time and continues to be revisited (e.g. Kang et al., 2015; Croll and Sugden, 2021).

If a case is made for Croll the Quaternary scientist, then it would be churlish to deny the potential claims of others who may be standing in line; for instance geographers (his nomination form for the Royal Society of London stated him to be an author of ‘many original and valuable contributions to Geology & Physical Geography’), Earth-system scientists and palaeoclimatologists. He was in the polymathic mould of his North American, autodidactical adversary, Simon Newcomb, or even of Alexander von Humboldt, though without the advantages of the German’s formal education and privileged background.

As an 1887 edition of the *Saturday Review* noted (Irons, 1896, p. 438):

Whatever objections may be fairly taken to certain of Dr. Croll’s positions, every honest scientific investigator will admit that his writings have had the most radical influence on cosmological speculation. In certain directions his influence has been nearly as great as that of Darwin’s in biology.

Such sentiments have been reprised by Fleming (2021, p. 5): ‘What Darwin did for life forms, Croll accomplished for climate change’; and ‘If Croll’s theory that the earth’s climate “revolves” around the sun started a Copernican revolution in climate dynamics, then Milanković served as the Newton of this field’ (Fleming, 2006, p. 52). Not bad epilogues for the self-educated son of a crofter–stonemason.

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Data Availability Statement

Data sharing is not applicable to this article as no new easily quantifiable data were created or analysed in this study. There are frequent references to either publicly available citation material or to archive documentary data which are accessible upon application to the repositories concerned. Relevant sources are indicated within the text.

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