

James Croll (1821–1890): ice, ice ages and the Antarctic connection

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Abstract: The thrust of this paper is that James Croll should be more generously lauded for his remarkable contribution to the study of ice ages, glacier flow and the nature of the Antarctic ice sheet. Croll was the first to calculate the link between fluctuations of the Earth's orbit and glacial/interglacial cycles, and to identify the crucial role of positive feedback processes necessary to transform minor insolation changes into major climatic changes. He studied the mechanisms of glacier flow and explained flow over horizontal land surfaces at a continental scale, including the excavation of rock basins. Croll relied on a quantitatively based deductive approach. One of his most remarkable achievements was his study of the thickness, thermal regime and dynamics of the Antarctic ice sheet (1879). This contains important insights, which are relevant today, and yet the paper was published before anyone had landed on the continent!

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Introduction

I am humbled to be asked to contribute to this special issue but welcome it as an opportunity to follow up a discovery at the 11th International Symposium of Antarctic Earth Sciences (ISAES) in Edinburgh in 2011. In preparation for a welcome to participants I entered the name James Croll into the University of Edinburgh author catalogue. Up came 24 entries with dates ranging from 1864–90. The immediate impression was of modern titles that, if included in a forthcoming programme of the American Geophysical Union (AGU) or European Geophysical Union (EGU), would attract great interest. As a glaciologist, my eye alighted on such titles as *On the physical cause of the motion of glaciers* (1869a) and *On the thickness of Antarctic ice, and its relation to that of the glacial epoch* (1879), the latter published before anyone had landed on the continent. As a physical geographer interested in the working of the Earth system, I already recognized the momentous work on the influence of orbital fluctuations on climate in the paper entitled *On the physical cause of the change of climate during geological epochs* (1864) and its full development in the classic *Climate and time in their geological relations: a theory of secular changes of the earth's climate* (1875). Here is the first integrated explanation of how minor changes in solar radiation due to orbital fluctuations are amplified by feedback to cause cycles of glacials and interglacials. Hints at the nature of the feedbacks are in titles such as *On the physical causes of ocean-currents* (1870a), while perspective on hemispheric asynchrony comes from the

paper *On the opinion that the southern hemisphere loses by radiation more heat than the northern, and the supposed influence this has on climate* (1869b). Not content with these powerful titles in the field of global geoscience, I could see extra-terrestrial forays such as *On the probable origin and age of the sun* (1877) and *Stellar evolution and its relations to geological time* (1889)! I could only wonder why I knew so little about this remarkable man (Fig. 1).

The aim of this paper is to focus on Croll's views of glacial/interglacial cycles, the connection with Antarctica and its ice cover, and the way possible changes in Antarctic ice volume are linked to global sea level. There are also some reflections on Croll's approach and methodology, as well as reasons for his fading reputation during his lifetime and the relative lack of recognition today.

Background

The life of James Croll is remarkable and it is difficult to improve on phrases in the opening paragraph of a review of his autobiographical sketch (Irons 1896), published in *Nature* in 1897. "That a mason's son, who in youth laboured on the few acres of his father's homestead; who then, having a mind disposed to mechanics, became apprentice to a millwright; ... having sometimes to walk thirty or forty miles a day to his work, and to sleep in a barn; ... found employment in the tea trade, ... set up a temperance hotel in a town, Blairgowrie, of 3500 inhabitants, with sixteen inns and public-houses there already, ... who, after a year and a half of failure as an innkeeper, took to canvassing for various insurance

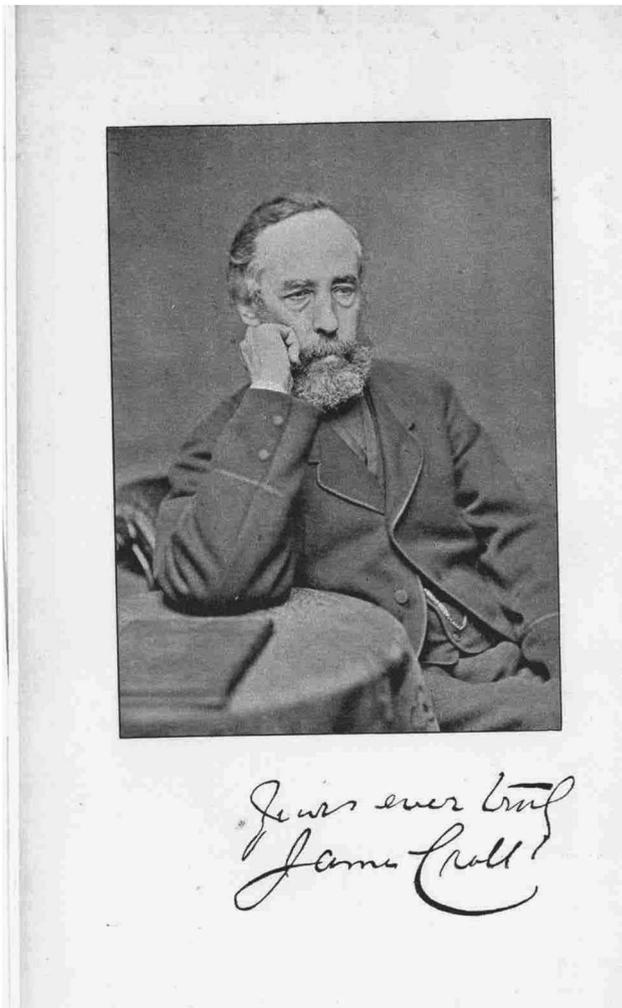


Fig. 1. James Croll signed this photo of himself for his friend James Campbell Irons, who compiled the *Autobiographical Sketch of James Croll* (1896).

companies, where as usual, everything went contrariwise with him - that such a man, who thus spent nearly the first forty years of his life, should have become so successful ... is perhaps not a matter of surprise, seeing that he was a Scotchman" (E.P.C. 1897, p. 362). Remarkably, Croll published in both philosophy and geology, and indeed he regarded his work on the former as his main contribution (Finnegan 2012).

The auspices for the world of geoscience were not bright when James Croll began to study. As he wrote about school, "I must say I was rather a dull scholar, scarcely up to the average of boys of the same age" (Croll, in Irons 1896, p. 12). Further, as he began his scientific work he noted, "There were two important and, to most people, interesting sciences for which I had no relish, namely, chemistry and geology, more particularly the latter ... Had anyone told me that one day I should become 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" (Croll, in Irons 1896, p. 14). There were two 'accidental' appointments which allowed him access to the latest publications in science and, most important, the time to read and develop his ideas. The first, in 1859 at the age of 38, was to the post of janitor at the museum in what was to become the University of Strathclyde. The second, at the invitation of Archibald Geikie, was to an administrative role in the Geological Survey in Edinburgh in 1867. Whilst in Glasgow he published the famous paper on the role of orbital fluctuations on glacial cycles. In Edinburgh, "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; for it enabled me to become acquainted with geological phenomena necessary for the subject" (Croll, in Irons 1896, p. 14).

Croll's appointment to the Geological Survey was nearly frustrated by the fact that he failed the Civil Service exam in arithmetic and English composition! Lord Kelvin was asked to write in support of his qualifications and in an obituary for Croll he later wrote, "the Civil Service Commissioners, with a wisely liberal relaxation of the rules, accepted his great calculations regarding the eccentricity of the earth's orbit and the precession of the equinoxes during the last 10,000,000 years as sufficient evidence of his arithmetical capacity, his book ... and numerous papers published in scientific journals as proof of his ability to write good English" (Irons 1896, p. 500).

Ice ages

James Croll is best known for his astronomical theory of climatic change. At the time he began his geological work in Glasgow there was a vigorous debate among geologists leading to the conclusion that the unsorted glacial drift or boulder clay so widespread in Scotland and in North America was deposited by land-based ice sheets, rather than by icebergs during a time of higher relative sea level. The latter view was championed by Charles Lyell, a leading geologist of the day, in early versions of his *Manual of elementary geology* (Hamlin 1982). Further, there were surprising fossil discoveries indicating warm climatic conditions within the glacial deposits pointing to interglacial episodes (Geikie 1863). Croll (1864) was the first person to develop a hypothesis that minor orbital fluctuations in the amount and distribution of solar radiation received by the Earth, due to eccentricity and the resulting precession of the equinoxes, could trigger feedback processes that could lead to cyclic glacial and interglacial states. Together these fluctuations modify both the length of a winter/summer season and the intensity of insolation received each season in both hemispheres. Croll used Leverrier's tables of orbital fluctuations to calculate the age of past glaciations and to predict future ice ages, the first attempt to derive a

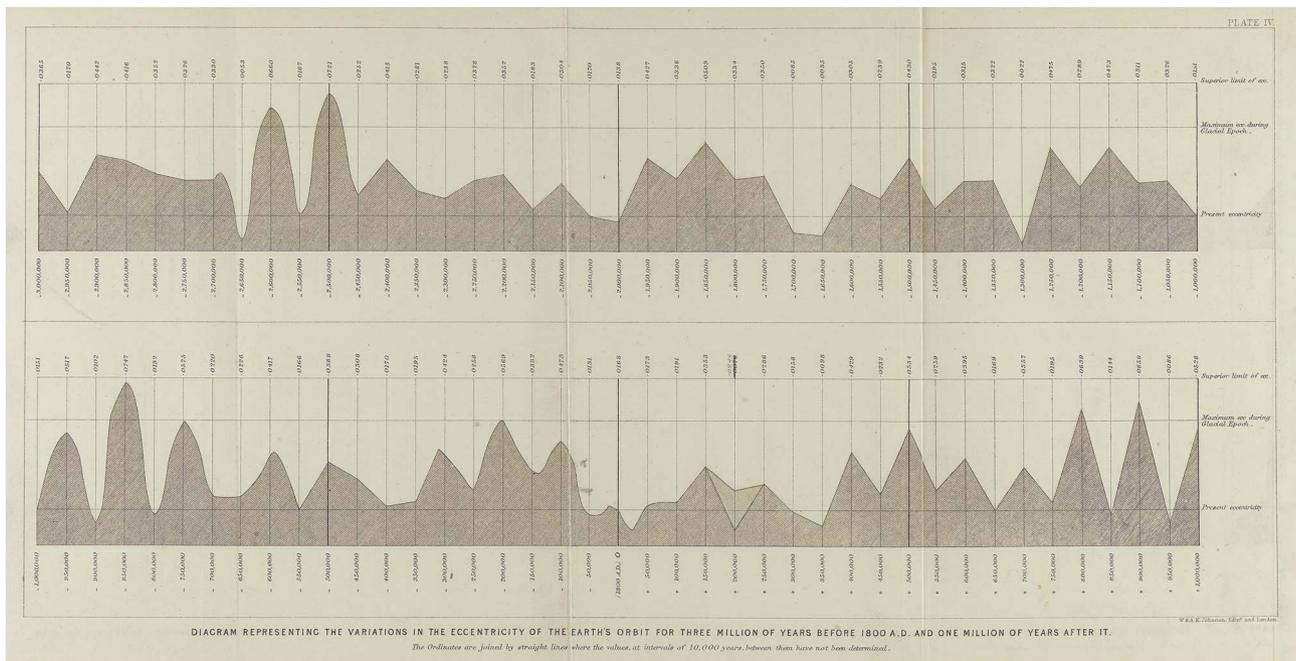


Fig. 2. Prediction of the variation in eccentricity of the Earth's orbit calculated by Croll using Leverrier's formula. Lower panel. The vertical line marked zero in the centre represents the year 1880 and the predictions to the right are for the next one million years. Predictions for the past one million years are to the left and show eight cold phases, a reasonable approximation of modern discoveries. Upper panel. Predictions from one million years ago (right) to 3 million years ago (left). Full glaciations occur at periods of high eccentricity, namely 2.6 and 2.5 million years ago and 850 000 years ago, while the next full glaciations are predicted to occur 800 000 and 900 000 years in the future. From Croll (1875, following page 312).

glacial chronology (Fig. 2). Identification of eight glacial cycles in the last million years was a path-breaking achievement and one essentially accepted today. An implication of the theory was that glaciations occur during periods of high eccentricity and that they are out of phase between the hemispheres. The theory was highly influential at the time and Charles Lyell revised his *Principles of geology* in response (Fleming 2006).

Later Croll developed the theory further by showing how longer-term variations in obliquity, or the tilt of the Earth's axis, are also involved (Croll 1875, Bol'shakov *et al.* 2011). "There is still another cause which, I feel convinced, must to a very large extent have affected climate during past geological ages. I refer to the change in the Obliquity of the Ecliptic" (Croll 1867a, p. 182). Croll, now convinced by geological evidence that interglacial states occurred in the past, for example, by descriptions of tree remains in the Arctic, argued that changes in obliquity would enhance the differences between hemispheres. "When the obliquity of the ecliptic was at a maximum, and 1/18th more heat falling at the poles than at present, the effect would be to modify to a great extent the rigour of glaciation in the polar zone of the hemisphere under a glacial condition, and, on the other hand, to produce a more rapid melting of the ice on the other hemisphere enjoying the equable climate. The effects of excentricity

and obliquity thus combined would probably completely remove the polar ice-cap from off the latter hemisphere, and forest-trees might then grow at the pole" (Croll 1867a, p. 188). It is worth quoting Croll's recognition of the role of obliquity since there is a popular view that it was left to Milankovitch to make this connection (Bryson 2004, p. 512).

Croll's major contribution was to agree with astronomers, such as Herschel (1835), that orbital insolation variations are too small on their own to play a direct role in climate change, but to suggest that there are important feedback processes that are triggered by such changes. This conclusion has resonance today when there is a tendency to correlate Milankovitch insolation variations at specific latitudes directly with geological records of climate change (Bol'shakov *et al.* 2011).

Croll recognized two possible feedback mechanisms. One such feedback mechanism was that ice and snow increased in the hemisphere with reduced winter insolation and that this further lowered temperatures, i.e. the albedo effect. He wrote that, "were the winter temperature very much reduced, it is obvious that what now falls during that season as rain, would then fall as snow. Under such circumstances it would be very doubtful whether the heat of summer would be sufficient to melt the snow of winter. Whether this would be the case

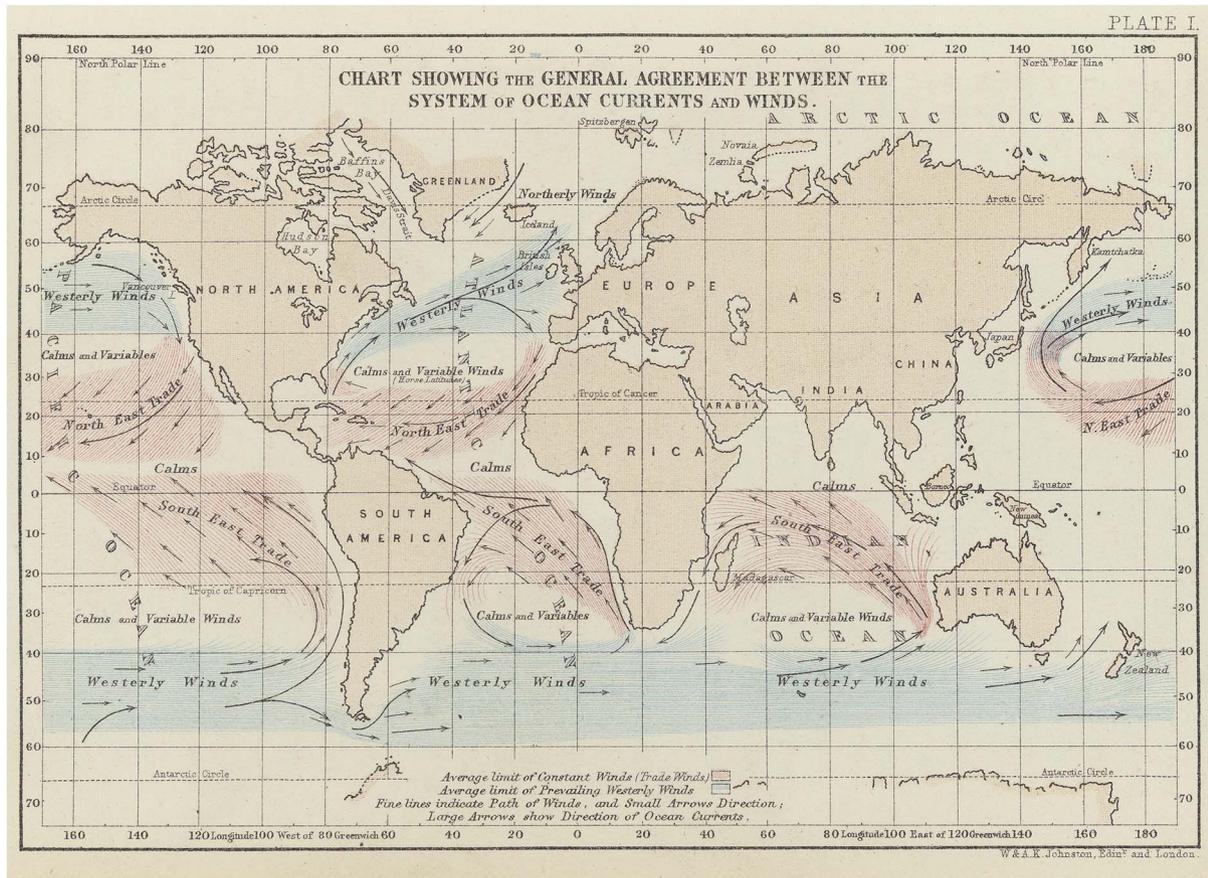


Fig. 3. “Chart showing the general agreement between the system of ocean currents and winds.” (Croll 1875, p. 213). It was this agreement that suggested to Croll that winds played an important role on ocean circulation. Lower temperatures in the polar regions of one hemisphere increase the strength of the trade winds and thereby ocean circulation; this leads to positive feedback since the increased turnover further cools the ocean, thereby enhancing the cooling of the atmosphere.

or not would depend on the nature of the summer ... if from thick fogs or an overcast sky the direct rays of the sun were prevented from penetrating the earth, the heat of the 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” (Croll 1864, p. 13). In support he quotes Captain James Cook’s description of South Georgia that “we thought it very extraordinary that an island between the lat. of 54° and 55° should at the very height of summer, be almost covered with frozen snow, in some places many fathoms deep” (Croll 1864, p. 14–15). Croll returns to the importance of the albedo effect in several papers. For example, “Were it not for the ice, the summers of North Greenland, owing to the continuance of the sun above the horizon, would be as warm as those of England, but instead of this, the Greenland summers are colder than our winters. Cover India with an ice-sheet, and its summers would be colder than those of England” (Croll 1870a, p. 30).

The next amplifying feedback in Croll’s view, and the most important, was that of changing ocean currents and

the effect these have on the transfer of heat between the hemispheres. This focus on the feedback provided by the oceans and especially the Atlantic was an early forerunner of the interest in the bi-polar seesaw which is very much the subject of modern debate about the synchrony of climate change between Antarctica and the northern hemisphere (Broecker 1998). Croll argued, in the face of the accepted wisdom, that ocean currents were driven primarily by winds rather than water density differences and that surface currents such as the Gulf Stream transported heat from the equator to the Arctic with a counter flow of colder water at depth (Fig. 3). Moreover his calculations showed that ocean currents were much more important than atmospheric circulation. “A greater quantity of heat is probably conveyed by the Gulf Stream alone from the tropical to temperate and arctic regions than by all the aerial currents which flow from the equator” (Croll 1867b, p. 10). Indeed, his calculations showed that, “the total quantity of heat conveyed by the Gulf-stream will probably nearly equal the amount received from the sun by the entire arctic regions” (Croll 1867a, p. 186).

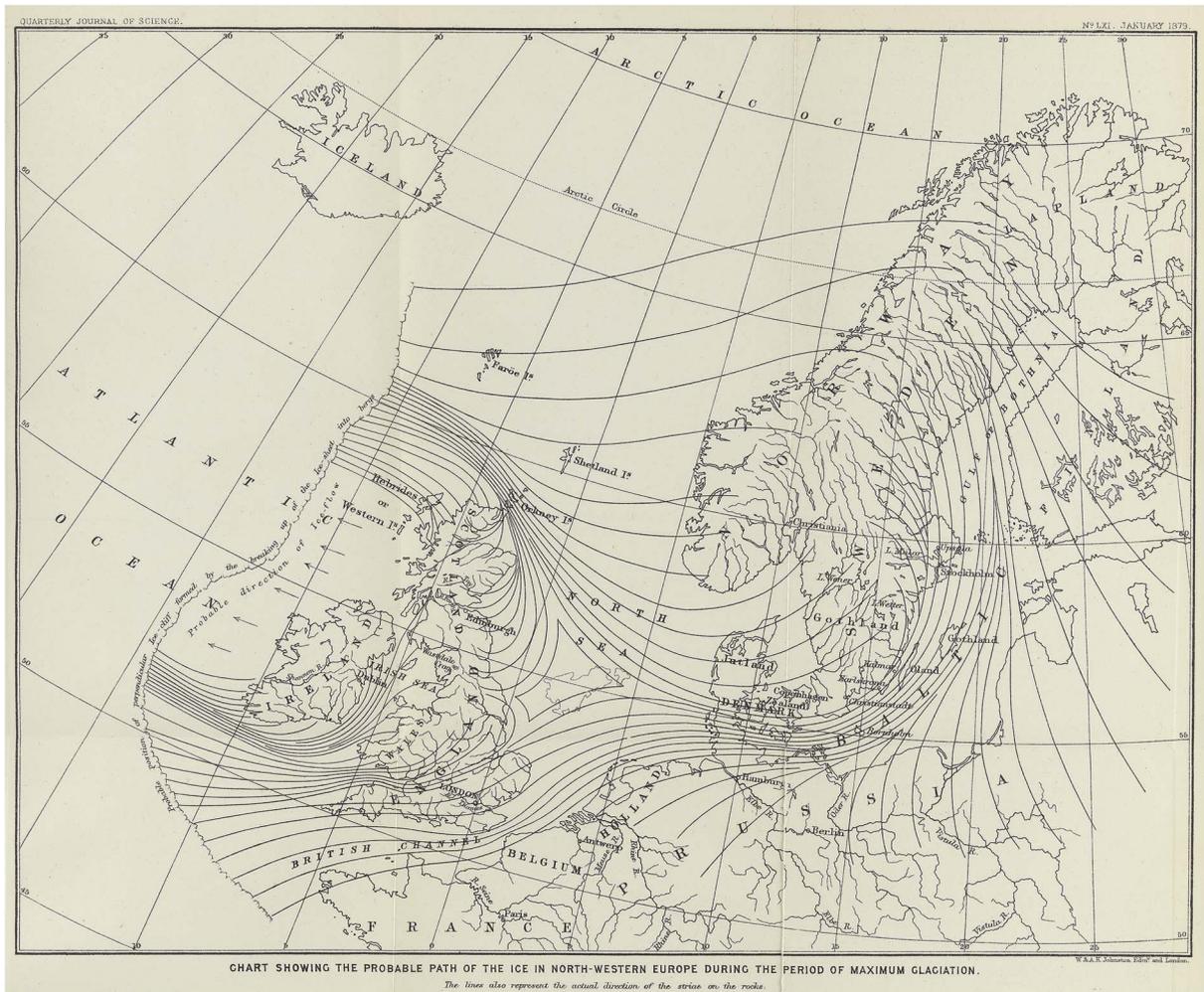


Fig. 4. Reconstruction of the former ice sheet in north-west Europe compiled by James Croll and used in his paper on the thickness of the Antarctic ice sheet. This reconstruction showed ice could cross basins and explained the transverse ice flow in Shetland and the onshore flow at the tip of Caithness, northern Scotland. The reconstruction is not too different to that now accepted, except that the inhabitants of unglaciated southern England will question whether he has been a little too enthusiastic! After Croll (1879, following page 34).

Feedback arises since the “hemisphere which has its winter in aphelion and under a condition of glaciation, is much colder than the opposite hemisphere which has its winter in perihelion and enjoying an equable climate” (Croll 1867b, p. 3–4). In the case of the northern hemisphere this increased temperature difference between the equator and the pole strengthens the trade winds and pushes them south. “The effect of the northern trades blowing across the equator to a great distance will be to impel the warm water of the tropics over into the Southern Ocean. And this, to an enormous extent, will tend to exaggerate the differences between the temperature of the two hemispheres” (Croll 1867b, p. 4). There is an additional related feedback effect in that “if the equatorial current of the Atlantic, the feeder of the Gulf-stream, were removed merely a few degrees to the south of the present position, the entire current would be turned into the Brazilian branch and flow into the Southern

Ocean, and thus probably stop the Gulf-stream altogether” (Croll 1867b, p. 4).

Croll devoted much effort to testing his hypothesis and developing understanding of its various components. Thus he examined boreholes in central Scotland to look for evidence of interglacials alternating with glacials, a key prediction of his hypothesis (Croll 1869c). In order to test his chronology, he used data on the sediment load of rivers as a means of establishing rates of land surface lowering and, by extrapolation, the age of surviving glacial deposits (Croll 1868). He closely followed progress in establishing the extent of mid-latitude ice sheets in Europe and North America, and indeed argued for the convergence of the former Scandinavian and Scottish ice sheets in the North Sea in order to explain the onshore ice flow in part of Caithness, northern Scotland (Croll 1870b) (Fig. 4); he noted that accepted views of glacier

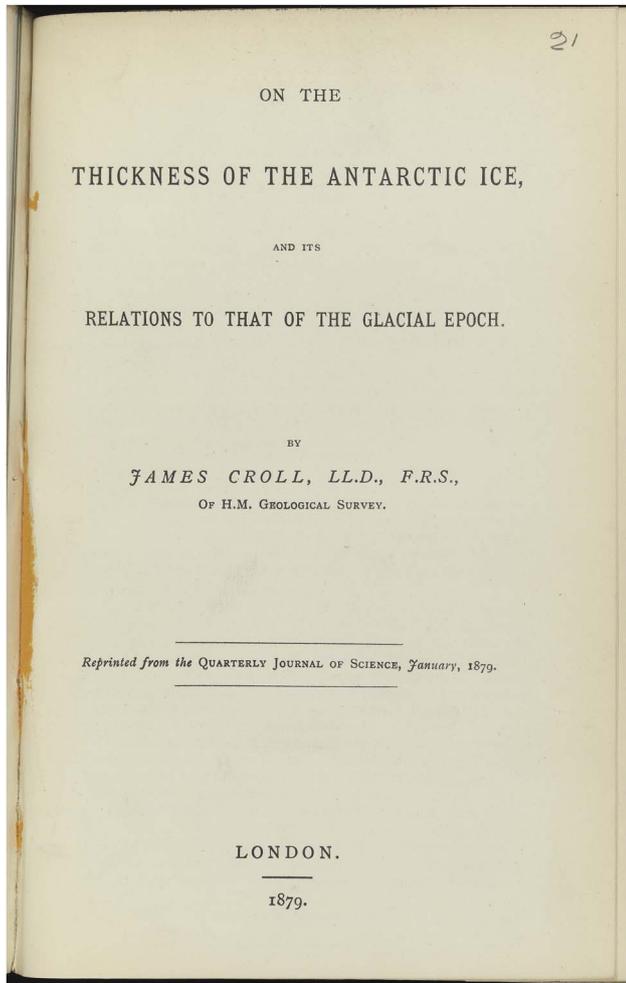


Fig. 5. The cover page of the impressive paper on the Antarctic ice sheet.

flow were unable to explain flow over flat continental surfaces (Croll 1875). Of particular significance to this paper, he became interested in Antarctica. On the one hand, it was demonstration of the asynchrony between the hemispheres with an ice sheet in one polar region and minimal ice in our present interglacial northern hemisphere. This asymmetry was a keystone to his theory. On the other hand, it was a current example of a large ice sheet whose study was important in understanding former Northern Hemisphere ice sheets and, if it fluctuated in size, a possible cause of eustatic changes affecting sea level in the Northern Hemisphere.

Ice

First, it was important to understand how ice flows. Croll's paper *On the physical cause of the motion of glaciers* (1869a) was prompted by an article by Canon Moseley, who recognized the occurrence of differential flow within a glacier was due to a shearing force, but that

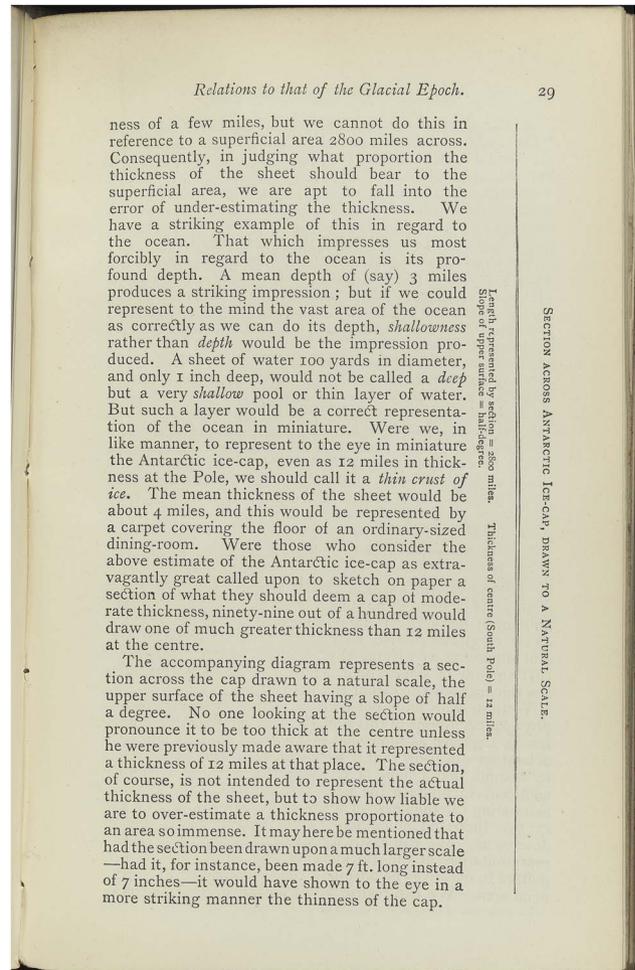


Fig. 6. Page extract from Croll's 1879 Antarctic paper in which he grapples with the issue of scale and perception. To the right of the text he draws a vertical cross section through the presumed Antarctic ice sheet assuming a thickness of 12 miles in the centre. As he explains in the lively text, it is not an unreasonable thickness if viewed at a continental scale. In a range of possible thickness reconstructions, Croll assumes a constant ice-surface gradient, which explains the high calculated thicknesses.

the weight of the glacier was 34 times too small to be the cause (Moseley 1869). This latter paper followed almost two decades of discussion in the literature as to whether glaciers flowed as a viscous substance rather like lava flows (Forbes 1843) or as a solid, with crevasses, sliding over the rock and striating its bed (Hopkins 1845). Hevly (1996) provides an overview of the debate. Croll argued that gravity was a sufficient force and that the explanation was because deformation within 'crystalline molecules' occurred as a result of a constant shearing. Further, crevasses are explained because they occur when crystals can no longer accommodate stretching. "The pull being continuous, the glacier will snap asunder the moment the cohesion of the ice is overcome" (Croll 1869a, p. 5).

Erosion by glaciers is unaffected since, “the grinding-effect is produced not by the ice of the glacier, but by the stones, sand, and other materials forced along under it” (Croll 1869a, p. 5). The important implication for Croll was that his molecular theory of glacier flow as a result of gravity explained why glaciers could flow over flat continental land surfaces and even erode rock basins.

Antarctica

Croll’s paper *On the thickness of the Antarctic ice, and its relations to that of the glacial epoch* (1879) is remarkable (Fig. 5). It considers and challenges previous hypotheses, discusses ice temperatures and ice flow directions, calculates possible ice velocities and ice thickness, compares the Antarctic ice sheet with mid-latitude ice-sheet reconstructions in the Northern Hemisphere and draws a cross section to scale to help convince a reader about statistics that are beyond our experience (Fig. 6). All this at a time when, “No one, as yet, has ever been able to set his foot on that continent; and the perpendicular wall forming the outer edge of its icy mantle is nearly all that has been seen of it” (Croll 1879, p. 3).

The background is a discussion about the thickness of tabular icebergs recorded by various ships’ captains and the way the horizontal layers within iceberg cliffs thin from top to bottom. Sir Wyville Thomson had argued that icebergs and the ice sheet from which they calved had a maximum thickness of 1400 feet (420 m), and that thinning of the layers was the result of progressive melting which eventually constrained the maximum thickness. Croll discusses the three main heat sources within an ice sheet, namely the ground, air and “work of compression and friction”, and gives a highly plausible description of the thermal regime of an ice sheet. “Besides, the ice has always a downward as well as a horizontal motion; for all the ice at the bottom comes primarily from the top, and that removed from below is replaced from above. Hence, not only is internal heat from below carried away by the horizontal flow of ice, but the upward motion of the heat is checked by a downward flow of ice from above;” (Croll 1879, p. 9–10). Further, “the temperature at which the ice melts is lowered by pressure at the rate of about 0.0137°F for every atmosphere of pressure” (p. 10), something he notes has been known since 1784. Bearing in mind probable cold surface temperatures, “it follows ... that the temperature of the great mass of the ice dome to near the bottom of the ice sheet must be considerably below the freezing-point” (p. 15).

There follows a discussion of the main flow patterns within the ice sheet and these advanced insights are well illustrated by two sub-headings: “*Continental Ice radiating from a Centre of Dispersion must be thickest at the Centre, and gradually diminish in Thickness towards the Circumference*” (p. 23), and “*The Greater Thickness of*

the Sheet at the Pole independent of the amount of Snowfall at that place” (p. 24). Each of these points is expanded in the text. Croll then estimates the velocity of ice at the margin based on the requirement to discharge the mean snow accumulation on the ice sheets. “Even supposing there were only 2 inches of ice discharged, the rate of motion would require to be between 400 and 500 feet per annum” (p. 26). The latter figure is equivalent to 120–150 m per year.

Croll based his estimate of the thickness of the Antarctic ice sheet, first by estimating the thickness of the outer edge on the basis of iceberg draft as 1400 feet (420 m). He then extrapolates inland, assuming a slope varying between 0.2 and 1 degree, the lower estimate yielding a thickness of 3 miles (4.6 km) and the higher estimate 24 miles (38 km). Each assumption is carefully discussed. He looks at 15 observations of iceberg height and quotes as an example “Feb., 1860 Captain Clark, of the *Lightning*, when in lat. 55° 20' S., long. 122° 45' W, found an iceberg 500 feet high and 3 miles long” (p. 5). Such a tabular iceberg cannot have rotated and thus its calculated thickness is a good representation of the ice thickness at the margin. Surface gradients and ice thicknesses were particularly difficult to establish and Croll made extensive use of evidence from Northern Hemisphere ice sheets and discussed gradients with both Archibald Geikie in Scotland and James Dana in North America. Croll notes that expeditions to the edge of the Greenland ice sheet record slopes rising inland and recommends that future expeditions go to the centre of Greenland to see how the gradient changes in the interior.

It is difficult to overestimate the novelty and power of this paper. At the time there was doubt about the existence of the Antarctic continent, never mind an ice sheet! For example, Joseph D. Hooker, the botanist who had accompanied James Ross into the Ross Sea and had actually been there, carried on a lively correspondence with Croll. In a letter written on 25 November 1883, Hooker summarized a series of objections with the words, “The burden of my tale is, that it is not right to speak of an Antarctic Continent at all, except as pure speculation” (Irons 1896, p. 407).

Sea level

When developing the argument about the role of obliquity, Croll realized that there would be an effect on global sea level. The apparent association of high sea levels with the presence of ice sheets had been long recognized in the Northern Hemisphere since the days of the iceberg theory of glacial drift, and subsequently backed by observations of raised beaches seen to accompany glaciations in areas such as Scotland, Scandinavia and North America. Croll argued that melting of the ice sheet in Antarctica at a time of Northern Hemisphere glaciation

could be an explanation. “It would evidently tend to produce an elevation of the sea-level on the northern hemisphere in two ways. 1st. The addition to the sea occasioned by melting of ice from off the Antarctic land would tend to raise the general level of the sea. 2ndly. The removal of the ice would also tend to shift the earth’s centre of gravity to the north of its present position - and as the sea must shift along with the centre, a rise of the sea on the northern hemisphere, would necessarily take place” (Croll 1867a, p. 190). The latter can be seen as representing the current view that the loss of an ice sheet would indeed have a global effect through the loss of the gravitational attraction of a seawater mass to an ice sheet (Clark *et al.* 1978). Such a relationship is crucial to predictions of sea-level change in a warmer world as demonstrated in the fifth Intergovernmental Panel on Climate Change (IPCC) report on climate change (Church & Clark 2013). Croll carried out calculations to show that the combined effect could help explain some of the raised beaches in Scotland.

Methodology

The most striking impression from reading the papers of James Croll is his clear deductive approach, but also the way he constantly linked his deductions to the real world. As he wrote, “at the very commencement of my studies, it was not the facts and details of the physical sciences which riveted my attention, but the laws or principles which they were intended to illustrate” (Croll 1896, p. 13). Most of his papers are structured around physical principles with an initial discussion of alternative interpretations and their limitations. The argument is usually developed mathematically and, where necessary, rests on assumptions or observations from the field which are scrutinized in detail. The remarkable power and clarity of Croll’s approach is illustrated by his prediction of the scale and dynamics of the Antarctic ice sheet before the continent had even been explored. All he lacked when estimating ice thickness at the centre was a realistic flow law for ice. Had Glen’s flow law (1955) been available 100 years earlier, doubtless Croll would have had the altitude of the centre closely constrained!

A second impression is the way Croll approached the subject from the perspective of the Earth system as a whole. His work involved links between astronomy, physics, oceanography, glaciology, geology, geomorphology and meteorology. Perhaps this breadth of interest is best illustrated by the range of chapter headings in his full work on *Climate and time* (1875). Apart from chapters central to his theory, such as astronomical variations and ocean currents, Croll also considers subjects such as denudation, age of the sun, thickness of sedimentary rocks on the globe, coal, and the motion of glaciers. This perspective helped him identify the principal mechanisms affecting the earth surface, especially those involving feedback, or what he

termed as ‘mutual reaction’. In correspondence he preferred the term over the alternative of ‘interaction’ because it implies an enhanced relationship, in other words positive feedback. In an interesting comment, Croll wrote, “It is quite a common thing in physics for the effect to react to the cause ... it is usually if not universally, the case that the reaction of the effect tends to weaken the cause ... But, strange to say, in regard to the physical causes concerned in the bringing about of glacial conditions of climate, cause and effect mutually reacted so as to strengthen each other” (Croll 1870a, p. 37).

Croll kept up a constant regular correspondence with other leading scientists, including Charles Darwin, John Tyndall, Charles Lyell, Alfred Wallace, Lord Kelvin, Joseph Hooker and Fridtjof Nansen. Though far from concise, the letters, the email equivalents of today, give an insight into the thinking of the time. For example, Charles Darwin asked, “Am I right in supposing that you believe that the glacial periods have always occurred alternately in the Northern and Southern Hemispheres so that the erratic deposits which I have described in the south parts of America and the glacial work in New Zealand could not have been simultaneous with our Glacial period? ... Secondly, do you believe that during the Glacial period in one hemisphere, the opposite hemisphere actually becomes warmer, or does it merely retain the same temperature as before? I do not ask these questions out of mere curiosity, but I have to prepare a new edition of my *Origin of species*, and am anxious to say a few words on this subject on your authority” (Irons 1896, p. 201–202). Croll responded by sending articles and his book.

Reputation

So the question arises as to why the reputation of such a respected and well-connected scientist faded away in his lifetime. A reviewer in *Nature* remarked “That which he [Croll] regarded as his most important and most conclusive work in physics - his glacial theory - has been steadily losing ground among geologists and physicists alike, and now it finds difficulty in securing a champion to fight its battles” (E.P.C. 1897). Further, in spite of the work of Imbrie & Imbrie (1986) and others, Croll’s contribution still seems undervalued today. For example, we often refer to the orbital theory of climate change as the *Milankovitch* theory rather than the *Croll-Milankovitch* theory.

One reason was the mismatch between theory and observations over chronology. For example, Croll (1864, p. 17) wrote, “We may safely conclude that it is considerably more than 100,000 years since the glacial epoch.” This of course is incorrect since much of the last 100 000 years coincided with the last glacial cycle. In hindsight this fundamental mismatch can be traced to Croll’s view that cold winters rather than cool summers explain glacial episodes. This was understandable but an unfortunate

assumption since it is the summer ablation gradient that is dominant in glacier survival (Schytt 1967). Croll may well have wished that he had listened to Mr Murphy whose paper *On the nature and cause of the glacial climate* argued that a cool summer had more to do with glacial conditions than a cold winter (Murphy 1869, Abstract). Croll's somewhat tetchy reply is perhaps revealing as he wrote, "The reason why we have so little snow, and consequently so little ice, in temperate regions, is not, as Mr. Murphy seems to suppose, that the heat of summer melts it all, but that there is so little to melt. And the reason why we have so little to melt is that, owing to the warmth of our winters, we have generally rain instead of snow" (Croll 1869b). Another reason for the mismatch between theory and observations was the evidence, as presaged by Darwin, that at least major glacials were in phase in both hemispheres.

The mismatch between theory and observations is not an adequate explanation of Croll's fading reputation at the end of his career. In effect, such mismatches are fundamental to the progress of science and, following the ideas of Popper (2002), the progress of science can be measured by the trail of discarded hypotheses. James Croll could and perhaps should have been hailed as the inventor of the astronomical theory of climate change, while his recognition of the importance of feedback processes within the earth system was an insight that we are still struggling to understand some 150 years later. Falsification of elements of the theory should have stimulated others to develop better theories.

Perhaps there are some clues to Croll's fading reputation in the obituaries following his death in 1890. Lord Kelvin commented on Croll's astronomical theory in the words: "This speculation undoubtedly presented a *vera causa* for some of the changes in climate which have occurred in geological history, although we can scarcely consider it adequate to be so powerful and exclusive a factor as Croll endeavoured to make it" (Irons 1896, p. 500). The obituary in *Nature* on Christmas Day in 1890 noted that Croll, "exposed without reserve views which seemed to him to be erroneous. With no intention of rousing controversy, he soon found himself in collision with other writers who disputed his arguments. One of the most interesting and vigorous of these disputations was with the late Dr. W.B. Carpenter regarding the theory of ocean circulation" (Irons 1896, p. 503). On this latter subject, the views of Croll have since proved fundamentally important. A more sympathetic obituary by J. Horne, of the Geological Survey of Scotland, notes that, "He has left behind him a brilliant series of researches" (Irons 1896, p. 505). But Horne also records that, "Though one of the most modest of men, he was a keen controversialist. The numerous replies to his antagonists appeared chiefly in *Nature* and *Philosophical Magazine*" (p. 518). So, a man who kept to himself,

avoided alcohol, made long solo walks armed only with paper and pencil, and rarely went to scientific meetings, seems to have attracted more than his share of controversy. Perhaps the controversial approach upset colleagues and lost him admirers.

Conclusion

Altogether, James Croll wrote 92 books and articles on the Earth system and how it functions. His 1864 paper and the all embracing book on *Climate and time* (1875) were exciting and probably decisive factors in his becoming elected a Fellow of the Royal Society in 1876. Croll's work demonstrates the power of a deductive approach, constrained by existing observations and testable by further observations. His paper on the form and behaviour of the Antarctic ice sheet, written before anyone had even landed on the continent, is testament to the power of his approach and made numerous predictions which were clearly testable (and many of them survived!). Above all, the work is characterized by the creation of bold hypotheses and tests, depth of thinking, clearly explained assumptions, and quantification where possible. Perhaps this self-educated man was just too far ahead of his time for his contemporaries to appreciate the depth of his originality.

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