

Reinterpretation of James Hutton's historic discovery on the Isle of Arran as a double unconformity masked by a phreatic calcrete hardpan

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ABSTRACT

Because it is partly masked by a phreatic calcrete hardpan (PCH), a rare and poorly known type of rock that can transgress stratigraphic boundaries, there has been ongoing controversy concerning the exact position of James Hutton's first discovered unconformity on the Isle of Arran in southwest Scotland. The unconformity separates folded Neoproterozoic to lower Paleozoic (Dalradian) metasedimentary rocks from upper Paleozoic red beds. The massive PCH developed in Late Devonian red conglomerate above the unconformity, but it also assimilated some of the underlying basement rocks, thus giving the false impression that the unconformity is at a lower position, as both host materials are almost entirely replaced by calcrete. At Hutton's discovery site, only a small remnant of the deeply calcretized Late Devonian conglomerate was preserved from erosion prior to being disconformably overlain by lower Carboniferous red conglomerate and sandstone. Thus, there are two unconformities at Hutton's historical site, but the younger has previously gone unnoticed, and the two red bed successions on each side of the disconformity were previously thought to belong to the same unit.

INTRODUCTION

The unconformable contact discovered by James Hutton in 1787 on the Isle of Arran, Scotland, was the first of this kind to be formally identified. It played a pivotal role in the development of ideas concerning the antiquity of the Earth and therefore has great historical significance. It has, however, received much less attention than the more photogenic unconformity identified later by Hutton at Siccar Point, east of Edinburgh. This is partly because the unconformable contact in Arran is obscured by massive calcrete, creating confusion as to its precise position.

There is no surviving detailed drawing from Hutton's time that would indicate where exactly he wished to place the contact, but when Archibald Geikie edited the third volume of Hutton's *Theory of the Earth* in 1899, he included such a drawing and placed the contact at the base of a tabular calcrete unit that is concordant with stratification in the sedimentary succession above the unconformity (Fig. 1A). On closer inspection, the structural grain of the Dalradian metasedimentary rocks that form the basement beneath the unconformity can be seen within the first meter of calcrete. Although this was pointed out by Anderson (1947) and Tomkeieff (1953), ambiguity concerning the exact position of the contact persisted, and Tomkeieff (1963) placed the contact at yet another (third) position. Young and Caldwell (2009) placed it higher than both levels suggested by Tomkeieff (1953, 1963), again reflecting the obscure nature of the contact due to the strong calcrete overprint.

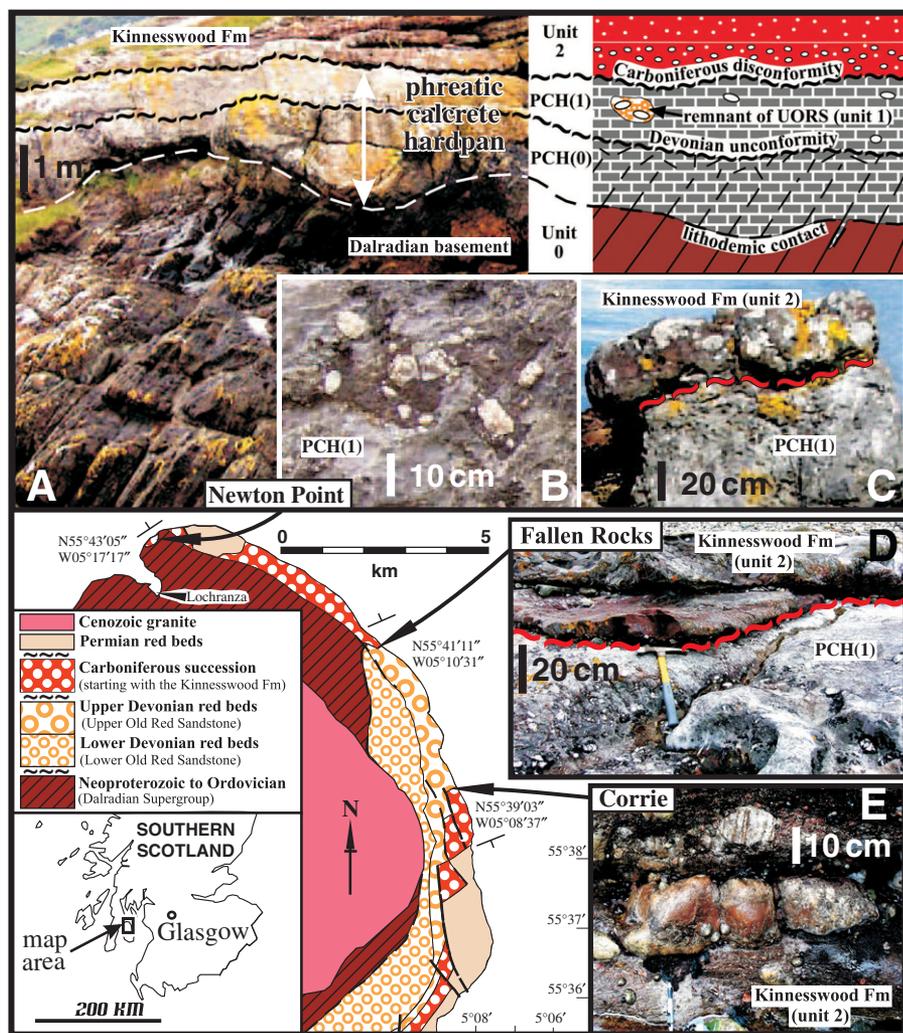


Figure 1. Simplified geological map of study area (modified from British Geological Survey, 1987), showing three studied localities. A–C: Hutton's angular unconformity (classical site) near Newton Point. A: General view and interpretive sketch. B: Window of non-calcretized conglomerate and quartz pebbles (unit 1, Upper Old Red Sandstone, UORS) in phreatic calcrete hardpan [PCH(1)]. C: Close-up of disconformable contact between PCH(1) and unit 2 (Kinnesswood Formation). D: Disconformable contact between PCH(1) and unit 2 at Fallen Rocks. E: Boulder of massive calcrete in basal bed of unit 2 at Corrie.

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In this paper, the petrogenesis, nature, and age of the calcrete at Hutton's Unconformity on the Isle of Arran are reinvestigated. We demonstrate that Hutton's first unconformity is in fact a threefold structure involving a Devonian unconformity, a latest Devonian–earliest Carboniferous lithodemic contact with a phreatic calcrete hardpan, and a previously undetected early Carboniferous disconformity.

FIELD RELATIONSHIPS

The Isle of Arran is one of a few localities in southwest Scotland where the contact between rocks of the Famennian Upper Old Red Sandstone and the lower Carboniferous Kinnesswood Formation can be observed. The contact is obscure because all of the rocks were deposited in a similar arid continental setting, which resulted in only subtle petrographic differences between the two units (Read et al., 2002). Both include polymictic red conglomerate and calcrete, but the Upper Old Red Sandstone tends to be coarser and more quartz rich. It also contains fewer and less strongly developed calcretes. The transition between the two units is thought to correspond approximately to the Devonian–Carboniferous boundary, but the lack of datable material makes this interpretation uncertain (Read et al., 2002). At Fallen Rocks, in northeast Arran, the Kinnesswood Formation is conformably overlain by marginal marine beds of the upper Tournaisian Ballagan Formation (British Geological Survey, 1987) and was therefore probably deposited well into the Tournaisian.

Stratigraphic relationships near the base of the Kinnesswood Formation were studied at Hutton's Unconformity near Newton Point (north Arran), at Fallen Rocks, and at Corrie (both in northeast Arran) (Fig. 1). Because the stratigraphy at that interval is rendered complex by overprints of regolith and calcrete within the succession, we simplify the reading by using numbers and acronyms that segregate lithostratigraphic units from lithodemic or pedostratigraphic units.

- Unit 0: low-grade metasedimentary rocks of the Dalradian Supergroup (Neoproterozoic to Early Ordovician) that were deformed by the Silurian to Devonian Caledonian orogeny, and that form the basement of upper Paleozoic successions on Arran (Read et al., 2002).

- Unit 1: the Devonian Old Red Sandstone.
- Unit 2: the early Carboniferous Kinnesswood Formation.

- PHC(0), PHC(1), and PHC(0,1): phreatic calcrete hardpan developed in, respectively, units 0, 1, or both; PCH(0,1) indicates that two lithostratigraphic units (0 and 1) now belong to one single lithodemic unit.

- VC(0): vadose calcrete developed in regolith of unit 0.

- VPC(1) and VPC(2): vadose and pedogenic calcretes developed in units 1 and 2, respectively.

Hutton's Unconformity Near Newton Point

At the classic locality of Hutton's Unconformity in north Arran, ~650 m northeast of Newton Point (Fig. 1), the section begins with the Dalradian (unit 0) strata, which dip ~55° toward the southeast and have a relatively sharp but irregular upper contact with a tabular mass of light gray calcrete that dips ~25° toward the northwest (Fig. 1A).

The thickness of the calcrete varies laterally from 2 to 2.75 m, but it is sharply eroded at the top and therefore incomplete. It includes rare windows of partially preserved host material, including in situ basement host rocks in its lowest 75–150 cm. In the basal 50–100 cm, these windows preserve the structural grain and color of the basement host rocks, but fragments of basement material are randomly oriented and increasingly oxidized in the succeeding 25–50 cm (Fig. 1A). The in situ basement material that is host to the calcrete probably represents a poorly developed regolith.

In the uppermost 75–125 cm of the calcrete, in situ basement rocks are absent, but rare windows of preserved host material are made up of coarse clastic sedimentary rocks with well-rounded pebbles and small cobbles. Locally, a grayish-red, coarse sandy matrix is preserved (Fig. 1B), indicating that the host material is a matrix-supported polymictic pebble conglomerate with nearly 50% coarse sand-size material. Although poorly sorted, the conglomeratic host rock of the calcrete has well-rounded clasts and is compositionally mature, with nearly 90% quartz pebbles. The petrography and stratigraphic position of this material correspond to that of the Upper Old Red Sandstone (unit 1).

Apart from these rare windows, most of the host material, including the siliciclastic framework, was thoroughly replaced by massive calcrete. Such thoroughness of mineral replacement over several meters in thickness is diagnostic of a PCH, the genesis of which involves an entire aquifer (Jutras et al., 2007, and references therein). The massive structure from base to top and the sharp lower contact with competent basement rocks (which is thought to correspond to the impermeable base of a paleoaquifer) are also typical of such calcretes, which have only previously been identified from the Quaternary of central Australia (Arakel and McConchie, 1982) and from the Visean of Atlantic Canada (Jutras et al., 2007). In this context of pervasive mineral replacement by phreatic calcrete, with only a small fraction of the original gravelly framework preserved, the presence of small remnants of more easily replaced red sandstone matrix, however rare and dispersed, suggests that the Upper Old Red Sandstone host material (unit 1) was already in part cemented at the time of calcrete formation.

Although the calcrete appears to be massive in outcrop, petrographic investigation reveals three distinct phases of formation. The earliest phase is dark gray micritic calcrete, which is locally replaced by a lighter gray micritic calcrete, and in part autobrecciated and incorporated into the latter. The third phase is white spar distributed in millimetric veins. Such complex textures are typical of PCHs and are thought to be due to alternating phases of precipitation and dissolution in laterally circulating groundwater that becomes increasingly obstructed as the calcrete is sealed (Arakel and McConchie, 1982; Jutras et al., 2007).

In terms of stable isotopes, samples from various levels of the calcrete [PCH(0,1)] at Newton Point (samples a and b in Fig. 2) show a well-constrained range of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values, although there is a tendency for the light gray late phase (b samples) to have lighter values than the dark gray early phase (a samples). The vein-like third phase is highly contaminated with small fragments of the earlier phases, and was therefore not analyzed for stable isotopes.

A sharp, slightly erosive contact is observed between PCH(0,1) and the concordantly overlying lower Carboniferous red beds of the Kinnesswood Formation (unit 2) (Fig. 1C). This disconformable contact was not previously recognized because of its near-planar nature, and because it is masked by the presence of calcite deposits along the planar, joint-controlled faces of the bedrock exposure. Hence,

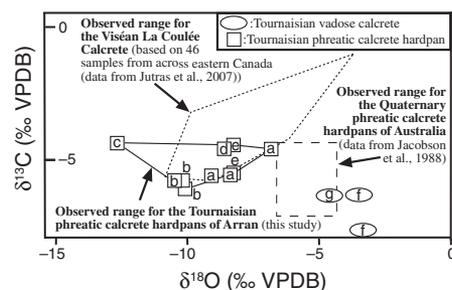


Figure 2. Stable isotopes of carbon ($\delta^{13}\text{C}$ Vienna Pee Dee belemnite, VPDB) and oxygen ($\delta^{18}\text{O}$ VPDB). In phreatic calcrete material [PCH(0,1)] at localities of Newton Point (a—early phase; b—late phase), Fallen Rocks (c), Corrie (d—in situ; e—reworked calcrete boulders in basal Kinnesswood, unit 2). In pre-Kinnesswood vadose calcrete from regolith [VC(0)] below Hutton's Unconformity (f—new, low-tide site), and in clast from the basal Kinnesswood conglomerate above (g; see Table DR1 in GSA Data Repository¹).

¹GSA Data Repository item 2011065, Table DR1 (carbon and oxygen isotopes in phreatic and vadose calcrete material at the Devonian–Carboniferous boundary on Arran), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

the lowermost red beds (unit 1; host to the PCH) and the disconformably overlying, lithologically similar succession of unit 2 were both thought to belong to the Kinnesswood Formation (British Geological Survey, 1987; Young and Caldwell, 2009), although both were previously assigned to the Upper Old Red Sandstone (Gunn and Geikie, 1947).

The Kinnesswood Formation (unit 2) at Newton Point is dominated by red sandstone with abundant vadose or pedogenic calcrete nodules and pillars [VPC(2)] (Young and Caldwell, 2009), which are typical of this unit in southwest Scotland (Read et al., 2002). The basal bed is a granular to pebbly sublitharenite with rare calcrete nodules, the dearth of which suggests that the erosional surface developed on PCH(0,1) was well washed prior to its burial by unit 2.

Although the paleosurface below unit 2 is only mildly undulating, with local surface topography of <30 cm (Fig. 1C), the deeply sculpted nature of the disconformity can be inferred from a new, low-tide exposure of Hutton's Unconformity that was identified by Young and Caldwell (2009) ~360 m west of the original site. There, PCH(0,1) is missing between units 0 and 2. Below the unconformity, the uppermost 1–2 m of basement rocks (unit 0) are deeply weathered, oxidized, and contain many calcrete nodules and veins. The structurally controlled distribution of calcrete suggests a nonpedogenic origin from groundwater, but diffuse and incomplete assimilation of the well-developed and thoroughly oxidized regolith points to calcrete formation in the vadose zone [unit VC(0)]. The stable isotopic signature of this vadose calcrete material is very different from that of the PCH at the classic site of Hutton's Unconformity, with lighter $\delta^{13}\text{C}$ and substantially heavier $\delta^{18}\text{O}$ values (f samples in Fig. 2).

The partly calcretized regolith [VC(0)] is sharply truncated by unit 2, which starts with a brick-red pebble conglomerate containing abundant clasts of the local basement and rare calcrete clasts. The contact is an erosive surface with a stepped paleotopography that displays irregularities as much as 75 cm deep. The only calcrete clast retrieved from this basal conglomerate (sample g in Fig. 2) shows $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values similar to those of the underlying vadose calcrete, and was probably derived from it.

Fallen Rocks Locality

The disconformable contact between PCH(1) and unit 2 is well exposed on a wave-cut platform beside the southernmost headland at Fallen Rocks (Fig. 1D), ~8 km southeast of Newton Point. This disconformity is above a thick succession of Devonian red beds (unit 1)

that, in turn, unconformably overlies Dalradian basement rocks (unit 0). In contrast with the Newton Point occurrence, the 1–1.5-m-thick calcrete remnant below the early Carboniferous disconformity at Fallen Rocks has a more diffuse lower contact, indicating that the base of the paleoaquifer was more poorly constrained above imperfectly cemented material. The calcrete is developed in a polymictic, but quartz pebble-rich Upper Old Red Sandstone conglomerate (unit 1) that was weathered prior to calcrete formation, as suggested by the destruction of sedimentary structures just below the calcrete and by the fragmented nature of weak sedimentary rock clasts. In terms of stable isotopes, PCH(1) at Fallen Rocks is very near the range of PCH(0,1) at Newton Point, albeit with slightly lighter $\delta^{18}\text{O}$ values (sample c in Fig. 2).

The top of PCH(1) at Fallen Rocks displays a sharp, eroded surface beneath unit 2 (Fig. 1D), which begins with a red pebbly sandstone with no calcrete clasts. Just as at Newton Point, unit 2 consists mainly of brick-red sandstone with abundant vadose or pedogenic calcrete nodules, pillars, and hardpans [VPC(2)].

Corrie Locality

At the Corrie locality, ~4.5 km south-southeast of Fallen Rocks, there is an erosional contact between units 1 and 2, but with a much more pronounced stepped paleotopography than at the other localities, and with massive calcrete [PCH(1)] that is only preserved in the least-deeply eroded areas of unit 1. PCH(1) from this area has $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values (sample d in Fig. 2) very similar to those of PCH(0,1) at Newton Point. At this site, large boulders of massive calcrete with a similar $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signature (samples e in Fig. 2) form the bulk of the basal conglomerate of unit 2 (Fig. 1E). Thus, the depositional surface was steeply dissected prior to and during deposition of unit 2, leaving resistant knobs of PCH(1) to be scavenged by streams.

DISCUSSION

The uppermost host material of the PCH at the classic Newton Point locality is lithologically similar to sandy conglomerate of the local Upper Old Red Sandstone (unit 1) and is interpreted to be a small remnant of that unit, spared from early Carboniferous erosion due to the resistant nature of such calcrete under arid climatic conditions (Arakel and McConchie, 1982; Jutras et al., 1999, 2007). Although only at Newton Point is the calcrete that is disconformably below the Kinnesswood Formation (unit 2) sufficiently well exposed to be firmly interpreted as a PCH, massive calcrete occurrences at Fallen Rocks and Corrie are at the same stratigraphic level, have similar $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values, and are probably part of the same

phreatic calcretization event. The age of the calcretization event is possibly latest Famennian, but because it occurs in a Famennian conglomerate (unit 1) that shows evidence of previous weathering at Fallen Rocks, and because the overlying Kinnesswood Formation (unit 2) could be as young as upper Tournaisian, it is more likely early or middle Tournaisian.

Such PCHs (or their dolocrete equivalents; Colson and Cojan, 1996, and references therein) are rare in the geological record. They are only known to develop in hyperarid climates by the mixing of fresh and salty groundwaters in the discharge zone into contemporaneous evaporitic basins, where the solubility of silicate minerals increases while that of calcite takes a sudden drop (Arakel and McConchie, 1982; Colson and Cojan, 1996; Jutras et al., 2007). Tournaisian evaporites are well documented in Scotland (Read et al., 2002), and therefore the model of Arakel and McConchie (1982) may also apply to the PCHs on Arran.

Stable Isotopes

All samples of the Tournaisian(?) PCH on Arran have $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values that are close to, or within, the range of values obtained from the Visean La Coulée Calcrete in eastern Canada (Jutras et al., 2007), although they have an overall tendency toward lighter values. They show no overlap with values from Quaternary occurrences of central Australia (Jacobson et al., 1988). This may be due to the very different nature of Quaternary vegetation, which directly influences the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of groundwater even in areas of very sparse cover, such as deserts. The tendency toward lighter values in the PCHs of Arran than in those of eastern Canada may reflect a slightly less arid setting for the former, as evaporation tends to concentrate heavy isotopes of both carbon and oxygen (Dever et al., 1987). The earliest calcrete phase in the PCH at Newton Point has heavier values than the younger one (Fig. 2), suggesting that the climate may have become decreasingly arid during the time of calcrete formation, culminating eventually in termination of the phreatic calcretization process.

Inferred Sequence of Events at Hutton's Unconformity in North Arran

1. Post-Caledonian erosion and weathering left truncated folds capped by poorly developed regolith in Dalradian basement rocks (unit 0) (Fig. 3A).

2. This surface was buried by red fluvial deposits of the lower to upper Devonian Old Red Sandstone (unit 1, Fig. 3B), which varies tremendously in thickness across faults on Arran.

3. According to petrographic evidence at Newton Point and at Fallen Rocks,

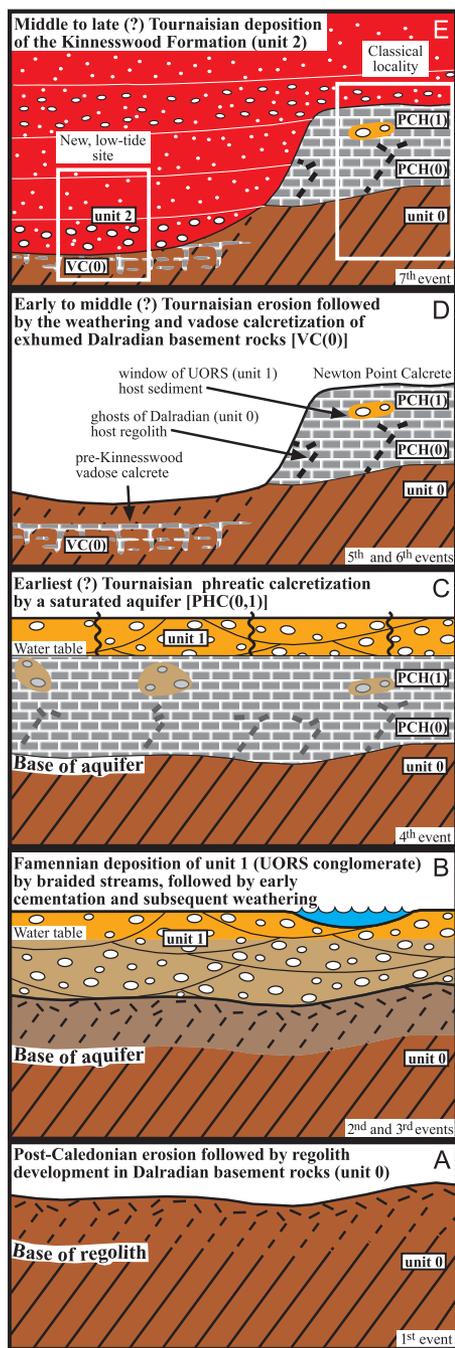


Figure 3. A–E: Inferred sequence of events for formation of Hutton's Unconformity near Newton Point (see text for discussion). PCH—phreatic calcrete hardpan; VC—vadose calcrete; UORS—Upper Old Red Sandstone.

conglomerate representing the youngest preserved Upper Old Red Sandstone (unit 1) on Arran was poorly cemented and subsequently weathered prior to phreatic calcretization (the next event).

4. The resulting regolith developed in unit 1 was calcretized by saturated phreatic water (Fig. 3C). At Hutton's Unconformity near Newton Point, the saturated aquifer penetrated

~1.5 m below the Caledonian unconformity into basement rocks (unit 0) (Fig. 3C). This led to the formation of a massive phreatic calcrete hardpan [PCH(0,1)], which assimilated regolith from both the basement and from the basal part of unit 1, leaving only rare dispersed remnants of the host materials (Fig. 3C).

5. The absence of PCH(0,1) at the new, low-tide site near Newton Point (Fig. 1F) suggests that this location represents a deeper erosional level than that seen at Hutton's original site, an inference that is supported by the presence of coarser deposits in the basal Kinnesswood Formation (unit 2) at this new site. The erosional event resulted in complete removal of unit 1 (Upper Old Red Sandstone) material that was above the water table (and therefore not subjected to phreatic calcretization), partial removal of PCH(0,1) at Hutton's original site, and complete removal in the case of the new, low-tide site (Fig. 3D). Such calcretes are typically 10–12 m thick in complete sections (Arakel and McConchie, 1982; Jacobson et al., 1988; Jutras et al., 1999).

6. The vadose calcrete and its red regolith host [VC(0)] at the low-tide site are interpreted to have been produced during a weathering event that followed erosion of PCH(0,1) (Fig. 3D), as they would have been unlikely to survive the phreatic calcretization event if they had developed previously.

7. The new regolith was eventually subjected to erosion and partly incorporated within basal beds of the Kinnesswood Formation (unit 2) (Fig. 3E).

CONCLUSIONS

At the classic locality of Hutton's Unconformity in north Arran, a complex geological history occurred between Caledonian deformation and the burial of folded and truncated Dalradian rocks by the early Carboniferous Kinnesswood Formation. Development of an erosion-resistant PCH allowed the preservation of some of that history. However, because they may transgress and mask lithologic boundaries, PCHs can also create problems in stratigraphic interpretations (e.g., Jutras et al., 2007, and references therein). The Newton Point occurrence is no exception, with its cryptic angular unconformity between Dalradian metasedimentary rocks and upper Devonian conglomerate (placed at three different positions successively by Tomkeieff, 1953, 1963, and Young and Caldwell, 2009), a lithodemic overprint by phreatic calcrete, which led A. Geikie (see Hutton, 1899) and subsequent generations of geologists to place the unconformable contact 1.5 m too low, and a previously unidentified disconformity between the PCH and early Carboniferous red beds, all within a section of <3 m.

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