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Rapid emplacement of a Palaeogene silicic volcanic centre, Arran, western Scotland.

Silicic volcanic centre emplacement

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Abstract

The timing and duration of silicic magmatism at relatively small volcanic centres in the geological record remain poorly constrained but are vital for understanding the temporal evolution of magmatic provinces. The Palaeogene Central Arran Igneous Complex (CAIC), and the nearby North Arran Granite, show spatial and temporal relationships between silicic intrusions and intra-caldera volcanic deposits. High-precision U-Pb zircon geochronology, integrated with detailed field observations, allows a timeline of silicic magmatic activity on Arran to be constrained. Silicic magmatism in north and central Arran occurred as a very short-lived (~0.5Ma) 'pulse' during the protracted (>8Ma) evolution of the British Palaeogene Igneous Province (BPIP). Evolution of the CAIC volcano from caldera collapse to

eruption of the youngest preserved unit (including several phases of eruption punctuated by quiescent periods of land surface erosion and deposition of sediments) took no more than 185ka. Silicic magmatism at the complex (volcanism followed by intrusion of granites) lasted no more than 330ka, with the North Arran Granite was emplaced shortly prior to the CAIC. This evidence of a short magmatic pulse accompanied by drastic land-surface changes has major implications for our understanding of localised silicic magmatism in other igneous provinces, both in the geological record and the present day.

1. Introduction

Recent significant improvements in the precision of U-series disequilibria and U-Pb geochronology can shed new light on the timescales of the development and evolution of upper crustal magma chambers and their associated eruptive products (e.g., Cooper, 2019; Curry et al., 2021). However, in relatively young volcanic systems which have not been significantly eroded to expose the remnants of upper crustal magma chambers, study of erupted and near-surface units will result in a temporally incomplete picture of the evolution of these central volcanoes. Conversely, substantial denudation of older volcanic-intrusive complexes may result in erosion of most eruptive units, with the consequent loss of a vital part of the temporal magmatic sequence. It is therefore important to identify and study central volcanoes that have been eroded enough to expose the upper crustal magma chambers, while still preserving much of the eruptive volcanic record. Such 'Goldilocks' volcano-magmatic complexes are likely to yield much more complete and precise timescales than very eroded or relatively recent volcanoes.

One such volcanic complex can be found on the Isle of Arran in western Scotland. It comprises well-exposed silicic intrusions and abundant volcanic rocks formed as part of the

British Palaeogene Igneous Province (BPIP). The BPIP (part of the larger North Atlantic Igneous Province) is a predominantly mafic Large Igneous Province (LIP) that formed between ~63 – 55 Ma during the initial rifting stages of the opening of the North Atlantic Ocean, and the arrival of the Iceland plume at the base of the lithosphere (e.g., Kent and Fitton 2000; Saunders et al. 1997; Storey et al. 2007, Wilkinson et al. 2016). Despite being volumetrically dominated by widespread mafic lavas and intrusions, the formation of the BPIP also comprised significant pulses of silicic magmatism, including granitic intrusions and rhyolitic ignimbrites (e.g., Brown and Bell 2013; Gooday et al. 2018; Meighan 1979; Troll et al. 2019; Drake et al. 2022). This silicic magmatism is largely confined to the spatially restricted ‘central complexes’ which can be up to 15 km in diameter (Emeleus 1982; Emeleus and Bell 2005). These complexes represent the eroded remnants of large discrete volcanoes and their plumbing systems, which occur on the islands of Arran, Mull, Skye, and Rum, the Ardnamurchan peninsula, and as several submerged offshore complexes.

These volcanic centres comprise a diverse range of intrusive and volcanic rocks, suggesting protracted magmatic histories. However, the lifespan and detailed chronology of these well-exposed remnant volcanoes remain relatively unknown. This paper presents detailed chronological information for the CAIC that reveals a hitherto unsuspected, relatively short timescale of emplacement and formation. This high-precision age data of volcanic and intrusive rocks, coupled with detailed field observations, has important implications for addressing many poorly understood aspects of silicic magmatism, particularly where it has occurred in largely mafic LIPs. These include: the mechanics of differentiation processes; the causes of magma migration; the likelihood and predictability of differing eruption styles; the effect of magmatic bodies on the thermal budget of the crust; estimates of magma

production rates; the role of silicic magmatism in LIP gas release, which in turn are vital for studies of crustal evolution and the effect of volcanism on climate (Bachmann and Huber 2016; Karakas et al. 2017; Black et al., 2021).

2. The Central Arran Igneous Complex

The Central Arran Igneous Complex (CAIC) was intruded into and erupted onto Palaeozoic sedimentary rocks (mostly sandstones) in what are now the hills of central Arran, an island in southwest Scotland (Fig. 1a). The CAIC is several kilometres south of the larger North Arran Granite, a texturally zoned laccolith intruded into the Neoproterozoic basement of north Arran (England, 1992; Stevenson and Grove, 2014). The CAIC itself comprises intrusive units of varying composition, and a caldera-fill succession of ignimbrites and sedimentary units (Gooday et al. 2018; Fig. 1b).

The caldera-fill succession (the Arran Volcanic Formation: Fig. 1c) records several phases of volcanic activity, with a range of eruptive styles, separated by periods of volcanic quiescence recorded by eroded palaeotopographical surfaces and the deposition of fluvial and mass-movement deposits (Gooday et al. 2018). Here we briefly summarise the descriptions of the members of the Arran Volcanic Formation provided by Gooday et al. (2018). The lowest exposed unit, the Muileann Gaoithe Member, comprises rhyolitic lava-like ignimbrites, some of which are exposed outside the caldera in the north east of the complex. Overlying this unit, the massive lapilli tuffs of the Allt Ruadh Member represent a highly explosive eruptive episode, probably related to the main phase of caldera collapse given the presence of caldera-wall debris flow conglomerates on its upper surface. The Creag an Fheidh Member and the Allt Beith tuff cone (Fig. 1c) are localised but represent varying magma compositions

and eruptive styles. The overlying White Tuff Member comprises rhyolitic lava-like ignimbrites, that are texturally and compositionally similar to the Muileann Gaoithe Member. The Pigeon Cave Member largely consists of massive lapilli tuffs and agglomerates containing lava-like cognate spatter clasts. This unit is overlain by a very coarse palaeo-canyon-filling debris flow conglomerate. The youngest preserved volcanic unit in the CAIC is the Ard Bheinn Member, a series of vitrophyric and crystal-rich tuffs.

The northern and eastern parts of the complex are dominated by a complex series of dioritic, gabbroic, and microgranitic intrusions (the Glenloig Hybrids, Fig. 1b) which display mingling, mixing, and intrusion relationships on a variety of scales. Several small (<1 km) granite intrusions are found within the complex, including isolated bodies around the margins of the complex (the Satellite Granites, Fig. 1b), which are petrographically and geochemically similar to one another (Gooday, 2018). A larger, geochemically distinct granite comprises much of the centre of the complex (Glen Craigag Granite, Fig. 1b).

Mafic dykes intrude the Glenloig Hybrids, the Glen Craigag Granite, and some apparently extra-caldera ignimbrites on the margins of the complex (Fig. 1b). They are not seen intruding the caldera-fill succession or the Satellite Granites. The North Arran Granite is dissected by multiple mafic dykes.

3. Samples and Methods

In this study, we present high-precision U-Pb zircon ages from seven units in the CAIC and two texturally distinct zones of the North Arran Granite: a coarser-grained outer zone

(sample BJG/15/179) and finer-grained inner zone (BJG/15/178). Four of the CAIC samples are from intrusive units: peripheral Satellite Granites from Bridge Farm (BJG/16/26) and Creag Mhor (BJG/15/347), the central Glen Craigag Granite (BJG/16/44), and a granitic vein intruding the Glenloig Hybrids (BJG/15/345). Three are from intra-caldera ignimbrites: the Allt Ruadh Member (BJG/15/3) from near the base of the succession, the White Tuff Member (BJG/15/14) from the middle of the succession, and the Ard Bheinn Member (BJG/15/142), the youngest exposed ignimbrite unit in the Arran Volcanic Formation. The locations of these samples are marked on figure 1.

Separated zircon crystals from these nine samples were annealed, leached, and dissolved, then isotope ratios measured on a Thermo-Electron Triton thermal ionisation mass spectrometer (TIMS) at the NERC Isotope Geoscience Laboratories at the British Geological Survey in Keyworth, UK (<https://www.isotopesuk.org/>). Data were analysed using the methods described by Condon et al. (2015) and McLean et al. (2015). Full analytical procedures (Appendix 1), data (Appendix 2) and representative CL images of zircons illustrating examples of magmatic zircons and those with rounded xenocrystic cores (Appendix 3) can be found in the supplementary material.

4. Results

All $^{206}\text{Pb}/^{238}\text{U}$ ages of individual analysed zircons are shown in Figure 2, along with weighted mean ages and zircon saturation ages (Keller et al., 2018). The raw geochronological data is reported in the supplementary material (Appendix 2). The interpreted $^{206}\text{Pb}/^{238}\text{U}$ age for sample BJG/15/14 is taken as the age of the youngest grain. All other samples take the weighted mean as the interpreted $^{206}\text{Pb}/^{238}\text{U}$ age. Weighted mean calculations for samples

BJG/15/142, BJG/16/26, BJG/16/44, BJG/15/178, and BJG/15/179 exclude older xenocrystic grains. The weighted mean calculation for sample BJG/15/3 excludes two grains which are interpreted to show young ages that reflect minor Pb loss.

Interpreted $^{206}\text{Pb}/^{238}\text{U}$ ages $\pm 2\sigma$ for the analysed samples are shown in Figure 3. These ages are taken as the age of eruption of the ignimbrite units, and the age of emplacement of the intrusions. All of these ages range from 59.0 to 58.7 Ma and reveal that all silicic magmatism in central and northern Arran occurred within a maximum of 470 ky. The results indicate that emplacement of the North Arran Granite (58.98 ± 0.06 Ma and 58.86 ± 0.07 Ma) predates the majority of magmatism at the CAIC (58.92 ± 0.19 Ma – 58.71 ± 0.07 Ma) but may have occurred synchronously with eruption of the caldera-fill ignimbrites (Fig. 4).

5. Discussion

5.1 Duration of Volcanism

Field mapping of the Arran Volcanic Formation shows a clear stratigraphy and therefore chronological sequence (Goody et al., 2018). The Allt Ruadh Member at the base of the succession and the Ard Bheinn ignimbrite have ages that are within error of each other, indicating that the entire caldera succession was emplaced in the time period 58.8-58.6 Ma. The interpreted $^{206}\text{Pb}/^{238}\text{U}$ ages of these units indicate that the maximum time between the episode of caldera collapse recorded by the Allt Ruadh Member and eruption of the youngest preserved caldera ignimbrites was 185 ky (Figs. 3, 4).

Within this short lifespan, the caldera would have been a highly dynamic landscape, with earth surface processes such as erosion, mass wasting and infilling of the caldera with

sediments, occurring rapidly during periods of volcanic quiescence (Fig. 5). Horizons between successive ignimbrite units are marked by development of significant palaeo-topography including hills, canyons, and fault-bound basins containing lakes. Deposition of intra-caldera sediments was widespread in the times between deposition of ignimbrites, as shown by preservation of sediments, breccias, and conglomerates on the upper surfaces of many ignimbrite units (Gooday et al., 2018). At least four cycles of ignimbrite eruption, erosion, and sediment deposition can be shown to have occurred within the 185 ky lifespan of the volcanically active caldera.

As well as various erosional and sedimentological processes at the surface, the period between caldera collapse and the youngest preserved caldera-fill rocks is characterised by large variations both in volcanic eruption styles and magma composition. Eruptions at the caldera varied in style from highly explosive plinian to low-fountaining 'boil-over' eruptions (Branney and Koeklaar, 2002). Explosive eruptions are recorded by the blanket of massive lapilli tuffs of the Allt Ruadh Member which covers the whole caldera. Less explosive low-fountaining eruptions are recorded by the lava-like ignimbrites of the White Tuff Member (58.753 ± 0.24 Ma), rocks which form during deposition of high temperature ($>900^{\circ}\text{C}$) pyroclastic density currents that have not entrained much cool atmospheric air (Branney and Kokelaar, 2002). Many of the other ignimbrite units show evidence for eruptions with explosivity between these two extremes, and often fluctuating in energy (Gooday et al., 2018).

The composition of magma erupted at the caldera varies from basic to silicic¹. The basaltic andesitic intra-caldera phreatomagmatic ignimbrite (the Allt Beith tuff cone) is underlain and overlain by rhyolitic ignimbrites (Fig. 1c; Gooday et al., 2018), suggesting a short period of less-evolved magmatism during the evolution of the caldera. This is important to the four-dimensional structure and evolution of the central Arran crust during this short (<185 ky) duration, as there must have been (presumably small and short-lived) basic magma sources and conduits supplying intra-caldera volcanoes without physically interacting with the silicic magma plumbing system.

5.2 Timing of intrusions in the CAIC

The ²⁰⁶Pb/²³⁸U ages of intrusions at the CAIC are all within error of one another, and so were emplaced at approximately the same time (within 340 ky, Fig. 3). The Creag Mhor Granite (58.723±0.09 Ma) and Bridge Farm Granite (58.682±0.13 Ma) belong to the petrologically and geochemically similar Satellite Granites. Both of these granites can be seen to intrude (and therefore post-date) the Allt Ruadh Member (Fig. 1). By this time (no more than 330 ky after deposition) the Allt Ruadh ignimbrites must therefore have been buried by tens to potentially hundreds of metres (Fig. 5). The emplacement ages of the Satellite Granites are within error of the interpreted eruption ages of the White Tuff and Ard Bheinn Member ignimbrites. This suggests that granites were being intruded into the caldera fill succession within a maximum of 170 ky of eruptive activity ceasing and may in fact have been coeval.

¹ The geochemical data can be found in Gooday (2018) and will be published in a forthcoming paper.

The Glen Craigag Granite in the centre of the complex has an interpreted emplacement age of 58.649 ± 0.17 Ma (Fig. 3). This overlaps with the ages of the Satellite Granites, from which it is petrologically and geochemically distinct. Field relations are poorly exposed and it is impossible to say whether the Glen Craigag Granite was intruded before or after eruption of the Allt Ruadh ignimbrites. The $^{206}\text{Pb}/^{238}\text{U}$ ages for these two units also overlap.

The youngest sample analysed from the CAIC was a granitic vein (emplacement age of 58.690 ± 0.09 Ma; Fig. 3) intruding the diorites of the Glenloig Hybrids which lie outwith and to the east of the caldera (Fig. 1). This provides a minimum age for intrusion of the main dioritic body of the Glenloig Hybrids. It is possible that these diorites pre-date volcanic activity at the caldera (Fig. 5), and field relations suggest they certainly pre-date the latest caldera subsidence (Gooday, 2018).

5.3 Age of the North Arran Granite

The two zircon ages for the North Arran Granite are within error of each other, suggesting more-or-less synchronous crystallisation throughout the whole intrusion. It is therefore not possible to prove or disprove by dating the hypothesis of Tyrell (1928) who suggested that the core of the intrusion is younger.

5.4 Chronology of Silicic Magmatism in Northern and Central Arran

Field relationships (albeit poorly exposed) such as the distributions of dykes and granitic veins suggest that the bulk of the Glenloig Hybrids and all mafic dykes intruding the CAIC may have formed earlier than the Allt Ruadh Member ignimbrites (Gooday 2018), and therefore prior to caldera volcanism (Fig. 4, 5). The high-precision $^{206}\text{Pb}/^{238}\text{U}$ ages presented

here for both volcanic and intrusive units in the complex overlap, and so cannot resolve the relative chronology. Intrusion of granitic magmas and eruption of rhyolitic ignimbrites were clearly occurring within a short timescale, but the precise order of events will require future detailed fieldwork and examination of the poorly exposed field relationships.

The emplacement of the North Arran Granite occurred immediately prior to, or coevally with, eruption of the lower intra-caldera ignimbrite units at the CAIC (Figs. 3, 4). The North Arran Granite has similar trace-element geochemistry to the White Tuff Member (and the lower Muileann Gaoithe Member), suggesting a cogenetic magma source (Gooday 2018). The geochemical homogeneity of both zones of the North Arran Granite, the Muileann Gaoithe ignimbrites, and the White Tuff ignimbrites most likely indicates a relatively long-lived rhyolitic magma reservoir that fed both a granitic laccolith to the north and a volcanic system to the south. The existence of a basaltic andesitic phreatomagmatic tuff cone stratigraphically positioned between the Muileann Gaoithe and White Tuff Members suggests that this long-lived rhyolitic magma reservoir existed at the same time, but spatially separate from, magma chambers of other compositions.

5.5 Spatial and Temporal relationships between the North Arran Granite and the CAIC

The North Arran Granite and the intra-caldera ignimbrites of the CAIC are today exposed at the same elevation, less than 3km apart at the closest point. This vertical juxtaposition of intrusions formed at depth (North Arran Granite) and surface deposits (ignimbrites at the CAIC) that were emplaced around the same time requires significant post-emplacement elevation changes. In the absence of significant Palaeogene or post-Palaeogene tectonic movements elsewhere on Arran, the CAIC caldera ring-fault is the most likely mechanism of

bringing coeval intrusive and erupted rocks to the same level. This means that downfaulting of the intra-caldera succession after eruption of the White Tuff Ignimbrites (the most geochemically similar to the North Arran Granite) must have been at least equal to the depth of emplacement of the North Arran Granite (assuming a relatively level palaeotopographical land surface). Estimates of caldera subsidence at the CAIC are on the order of 1 km (Gooday 2018; King 1954) and this can therefore be taken as a first-order approximation of the depth of intrusion of the North Arran Granite.

5.6 Wider implications

The CAIC has proved a particularly insightful study location regarding the timing of the formation of a volcanic and intrusive complex, largely due to its ‘Goldilocks’ level of erosion and present exposure. The hitherto unrecognised relatively rapid formation of the CAIC has potential impacts not only on our understanding of the other volcano-intrusive complexes in the province, e.g., Skye, Rum, Mull and Ardnamurchan, but also has implications for bimodal mafic/silicic volcanic systems throughout the geological record.

Rapid punctuation of longer-term basaltic magmatism by large silicic volcanic eruptive episodes is consistent with evidence from the Afro-Arabian LIP (e.g., Roobol and White, 1986; Kellogg, 1985). Large caldera-forming silicic eruptions occurred at the Tana Basin in Ethiopia and in Northern Yemen, where short (not more than 330 ky and 340 ky, respectively) episodes of silicic volcanism were preceded and succeeded by longer-lasting periods of mafic and bimodal magmatism (Prave et al., 2016, Thines et al., 2021). While larger systems than the CAIC, these maximum lifetime timescales are remarkably similar to our findings from Arran.

294

295 Another predominantly mafic LIP with rapid emplacement of silicic units is the Paraná
296 Magmatic Province of Brazil, when all silicic volcanism has been dated with high-precision U-
297 Pb zircon to a time period of around 700 ky (Rocha *et al.*, 2020). Despite high volumes of
298 silicic volcanism and very high magma eruption rates (in both the Paraná and Afro-Arabian
299 provinces), these episodes of silicic magma emplacement have been temporally correlated
300 with periods of significant climatic change. Although it is impossible to estimate total
301 erupted magma volumes in the case of Arran (due to erosional loss of almost all extra-
302 caldera ignimbrites), the preserved intra-caldera units suggest that erupted volume and
303 eruption rates must both have been relatively high. It is therefore interesting to note that
304 the CAIC formed before the Paleocene-Eocene Thermal Maximum, while a later volcanic-
305 metamorphic system in the BPIP (the Kilchrist caldera system in Skye where thermal
306 metamorphism of carbon-rich sedimentary rocks caused release of CO₂ into the
307 atmosphere) has been correlated with this climatic warming event, as has activity
308 throughout the rest of the North Atlantic Igneous Province (Drake et al., 2022; Jones et al.,
309 2023).

310

311 Similar detailed mapping and high-precision geochronology should be carried out on the
312 other BPIP central complexes to determine if such rapid formation is common throughout
313 the province. Furthermore, volcanic lifecycles of a few hundred thousand years are likely to
314 have more of a local and regional environmental impact than longer-lived volcanic
315 complexes. In the late Pleistocene and Holocene such rapid-scale eruptions may well have
316 led to population migration and the decline of civilisations e.g., the Mayan –(Kees Nooren et
317 al. 2017) and Minoan civilisations (Tsonis et al. 2010). Recognising the short-lived nature of

such volcanic-intrusive systems will lead to better understanding of volcanism in the geological record as well as improving our understanding and modelling of currently-active systems and future eruptions.

6. Conclusions

Our high-precision U-Pb data show that silicic magmatism in central/northern Arran (Central Arran Igneous Complex and North Arran Granite) occurred over a remarkably short timescale between around 59.0 and 58.5 Ma. The maximum lifetime of the CAIC, from the initial phase of caldera volcanism to the intrusion of the youngest post-caldera intrusions, was 330 ka. Volcanic activity at the complex, from caldera collapse to eruption of the youngest preserved ignimbrites, lasted no more than 185 ky. During this period there were several cycles of ignimbrite deposition, landscape erosion, and deposition of intra-caldera sedimentary horizons, as well as varying eruptive styles and compositions of erupted material.

Emplacement of the North Arran Granite took place no more than 200 ky earlier than volcanic activity at the CAIC, suggesting that significant post-volcanic subsidence must have occurred at the caldera to bring both systems to the same current elevation.

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Figure Captions

- Figure 1 – **a)** Outline map of Arran showing the positions of the North Arran Granite and the Central Arran Igneous Complex, and the position of Arran within Scotland (inset) **b)** Simplified geological map of the Central Arran Igneous Complex (from Gooday *et al*, 2018) **c)**

471 Stratigraphic log of the caldera fill succession of the CAIC (from Gooday *et al*, 2018). Sample
472 locations are marked by zircon-shaped symbols and numbers on the maps and stratigraphic
473 column. The location numbers refer to the following samples: 1 - BJG/15/178; 2 -
474 BJG/15/179; 3 - BJG/15/347; 4 - BJG/15/3; 5 - BJG/16/26; 6 - BJG/15/14; 7 - BJG/15/142; 8 -
475 BJG/16/44; 9 - BJG/15/345.

476

477 Figure 2 – Results of ID-TIMS U-Pb dating of Arran zircons, showing $^{206}\text{Pb}/^{238}\text{U}$ ages of
478 individual analysed zircons

479

480 Figure 3 – Interpreted $^{206}\text{Pb}/^{238}\text{U}$ ages for dated units of the CAIC and the North Arran
481 Granite

482

483 Figure 4 – Chronostratigraphic chart showing the temporal relations between the erupted
484 and intruded units of the CAIC and the North Arran Granite

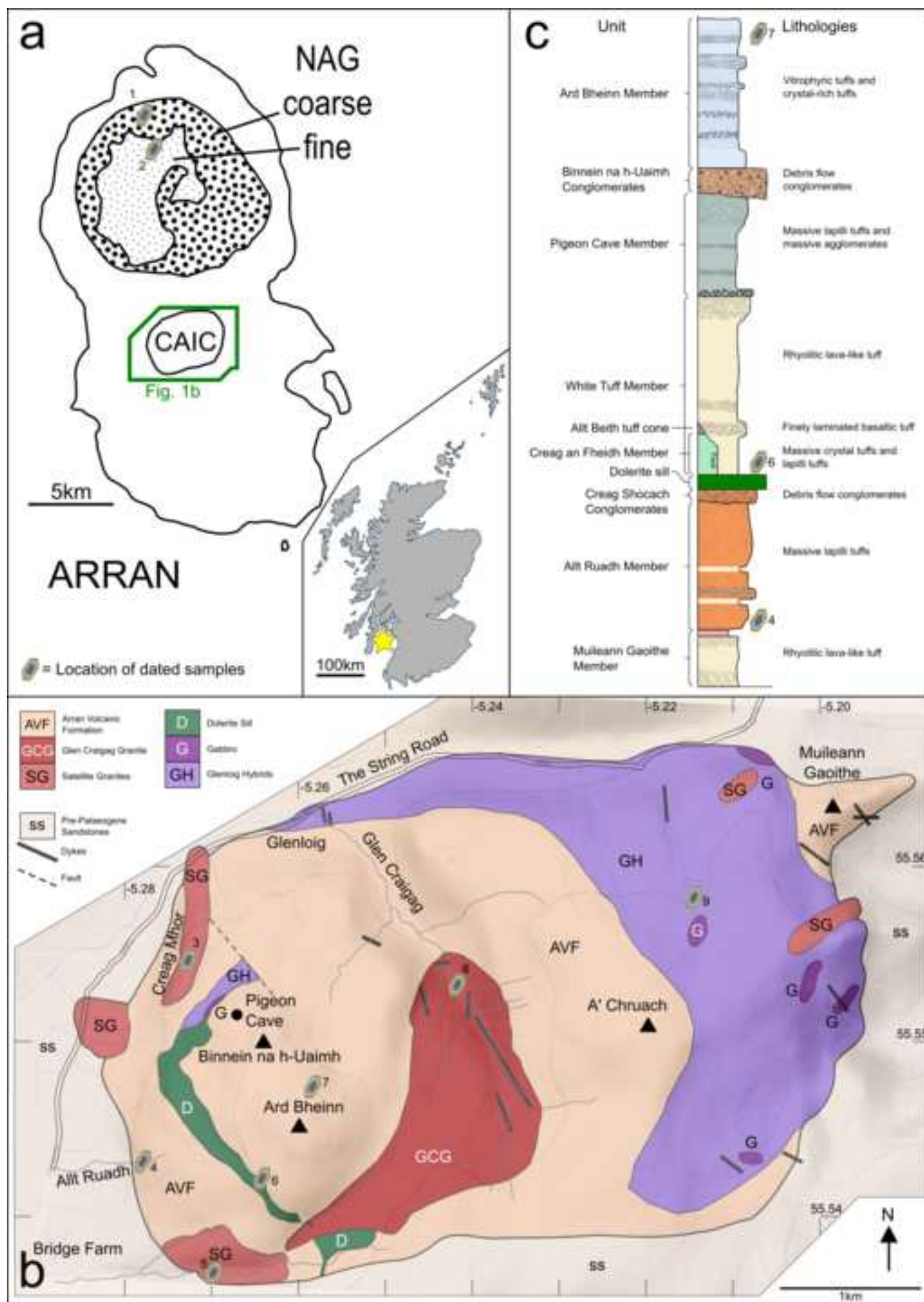
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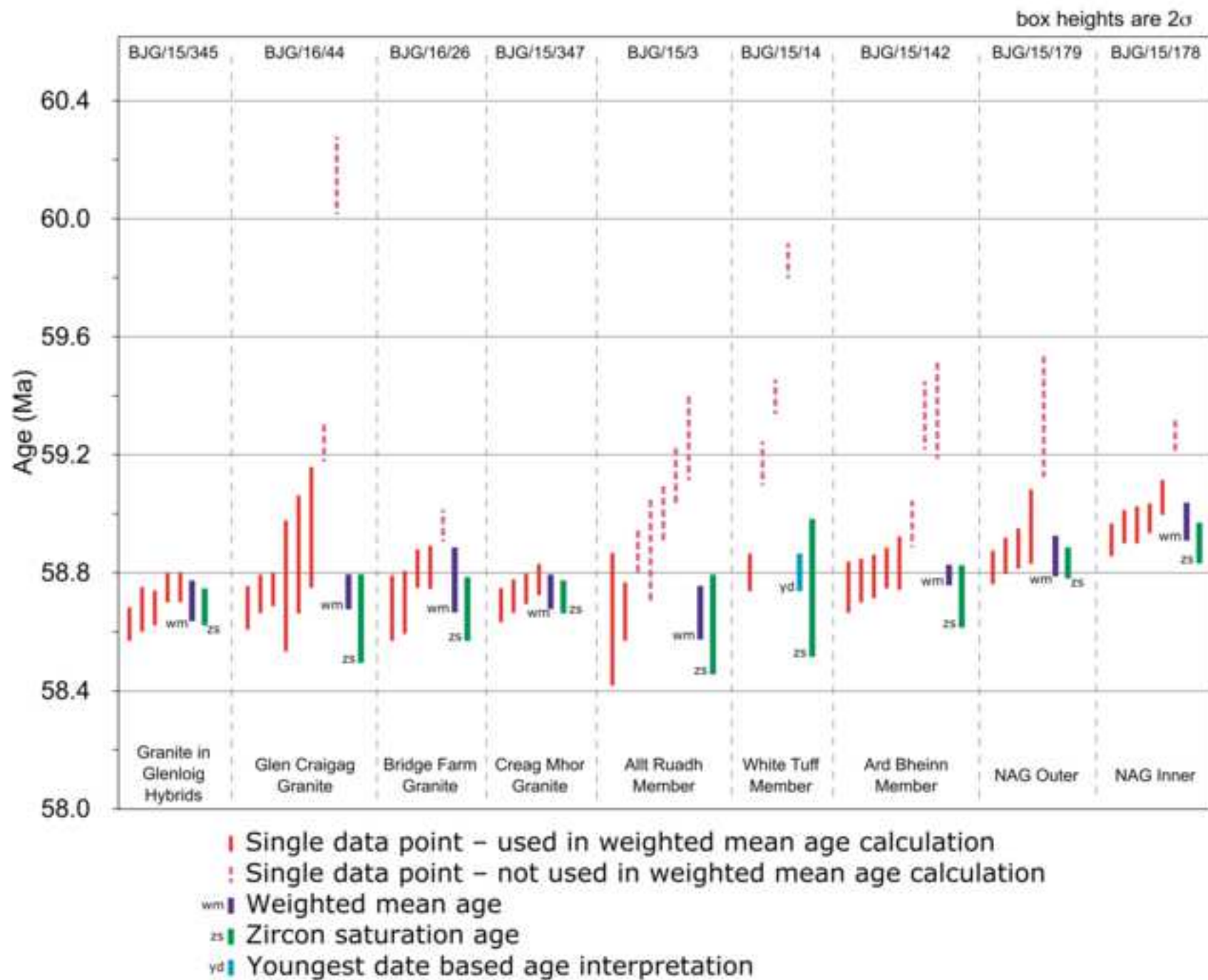
486 Figure 5 – A possible timeline of cross sections showing the spatial evolution of the intrusive
487 and volcano-tectonic activity in north and central Arran in the ~400 ky between 58.9 and
488 58.5 Ma. Due to the rapid evolution of the system and the scale of uncertainty on individual
489 interpreted zircon dates, precise dates for each stage are not possible. **a)** The North Arran
490 Granite is intruded as a laccolith (Stevenson and Grove, 2014) into pre-Paleocene
491 sedimentary and metamorphic rocks, first the finer-grained inner portion followed by the
492 relatively coarser outer zone. The diorites of the Glenloig Hybrids may have been intruded
493 around this time, or already existed. **b)** Volcanism at the CAIC begins with caldera collapse
494 and eruption of the Allt Ruadh Member tuffs and breccias. **c)** Earth-surface processes such

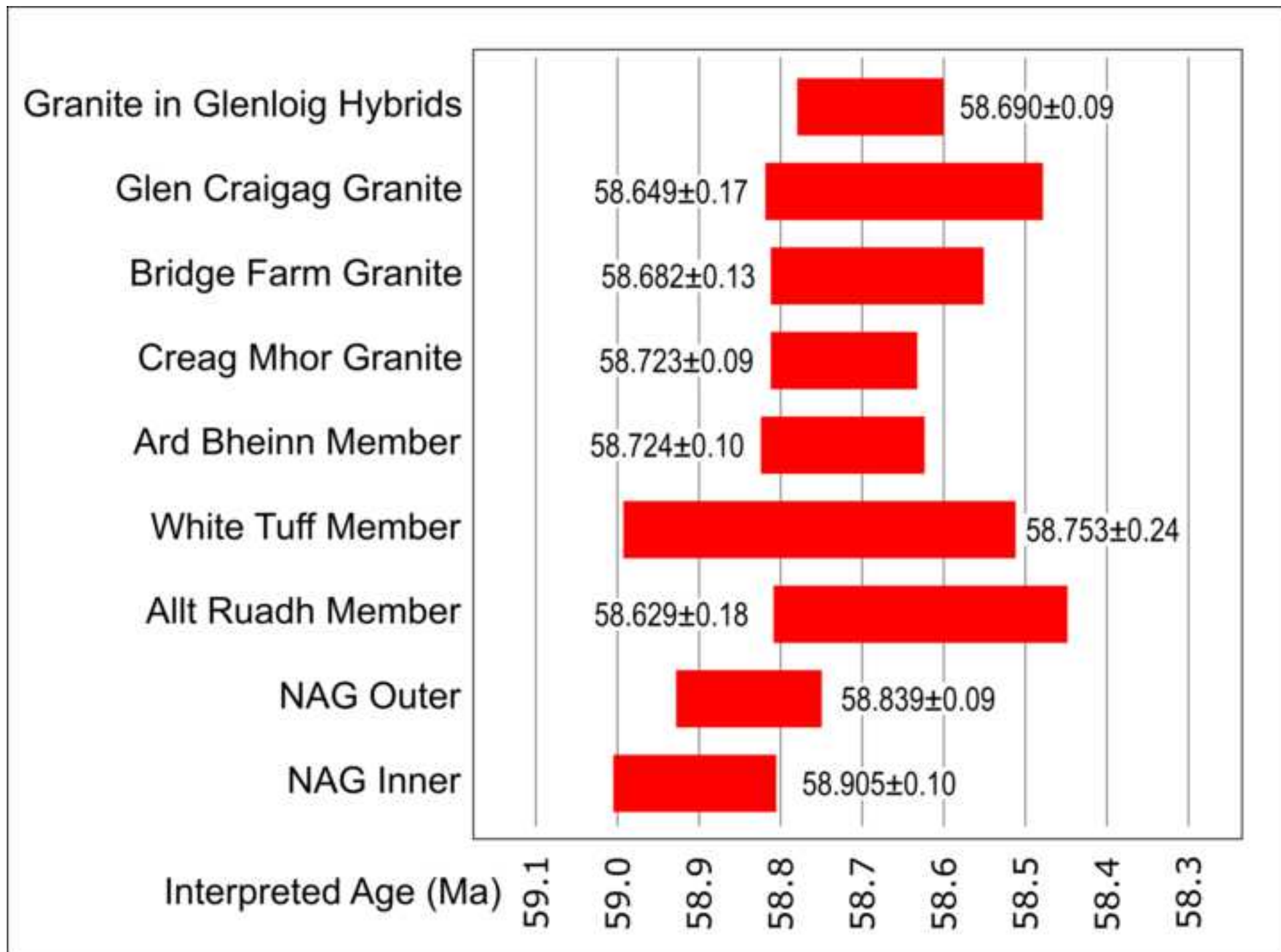
495 as erosion, caldera-wall collapse, and sediment deposition occur before eruption of the
496 White Tuff Member lava-like ignimbrite. **d)** More earth-surface processes, and eruption of
497 smaller volcanic units, occurs before final eruption of the Ard Bheinn Member tuffs. **e)**
498 Continued subsidence at the caldera caused burial of the volcanic and sedimentary rocks of
499 the Arran Volcanic Formation and brings them to their current level alongside the North
500 Arran Granite. **f)** Intrusion of granites into the Arran Volcanic Formation units that were
501 recently formed at the Earth's surface.

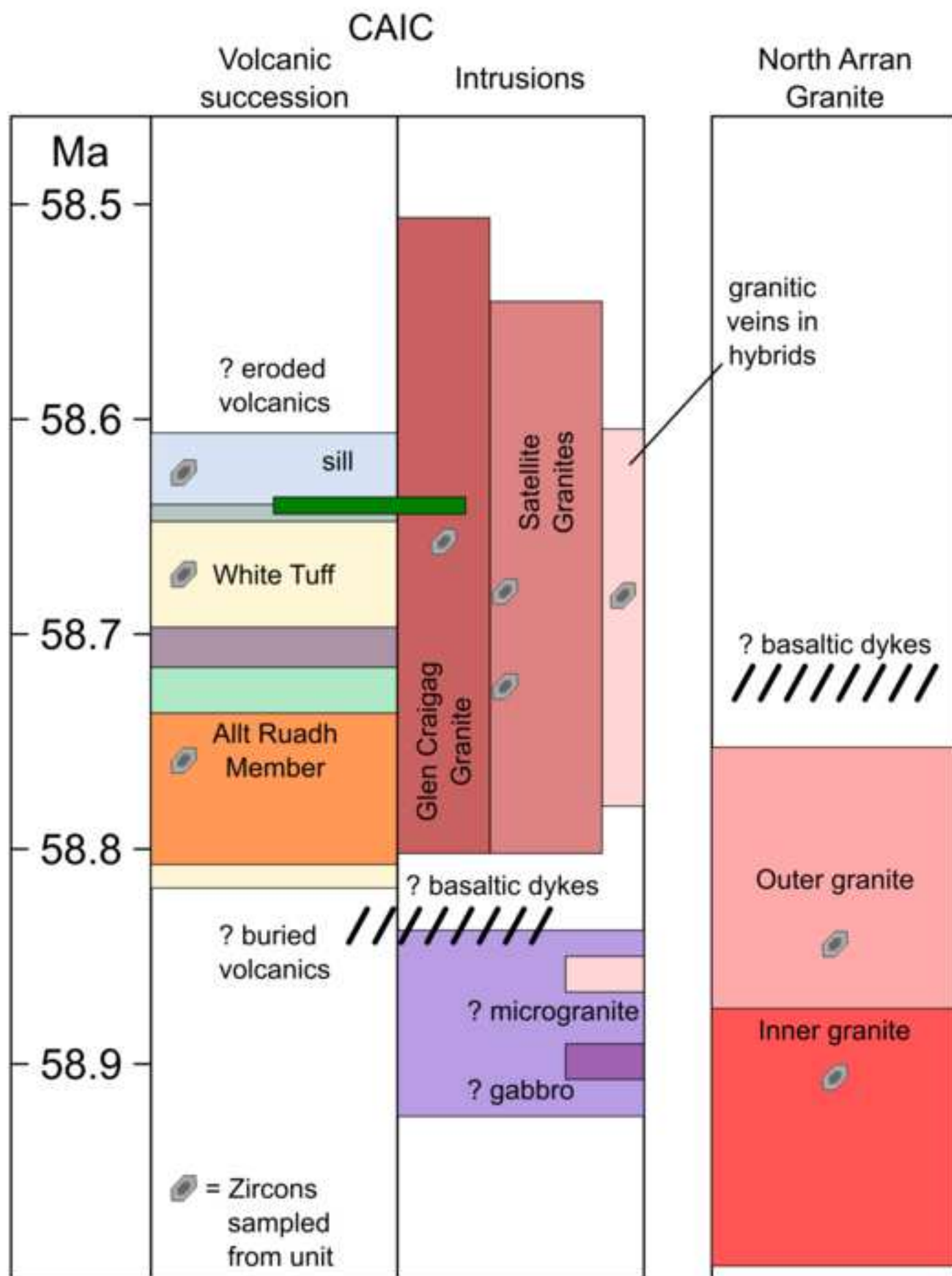
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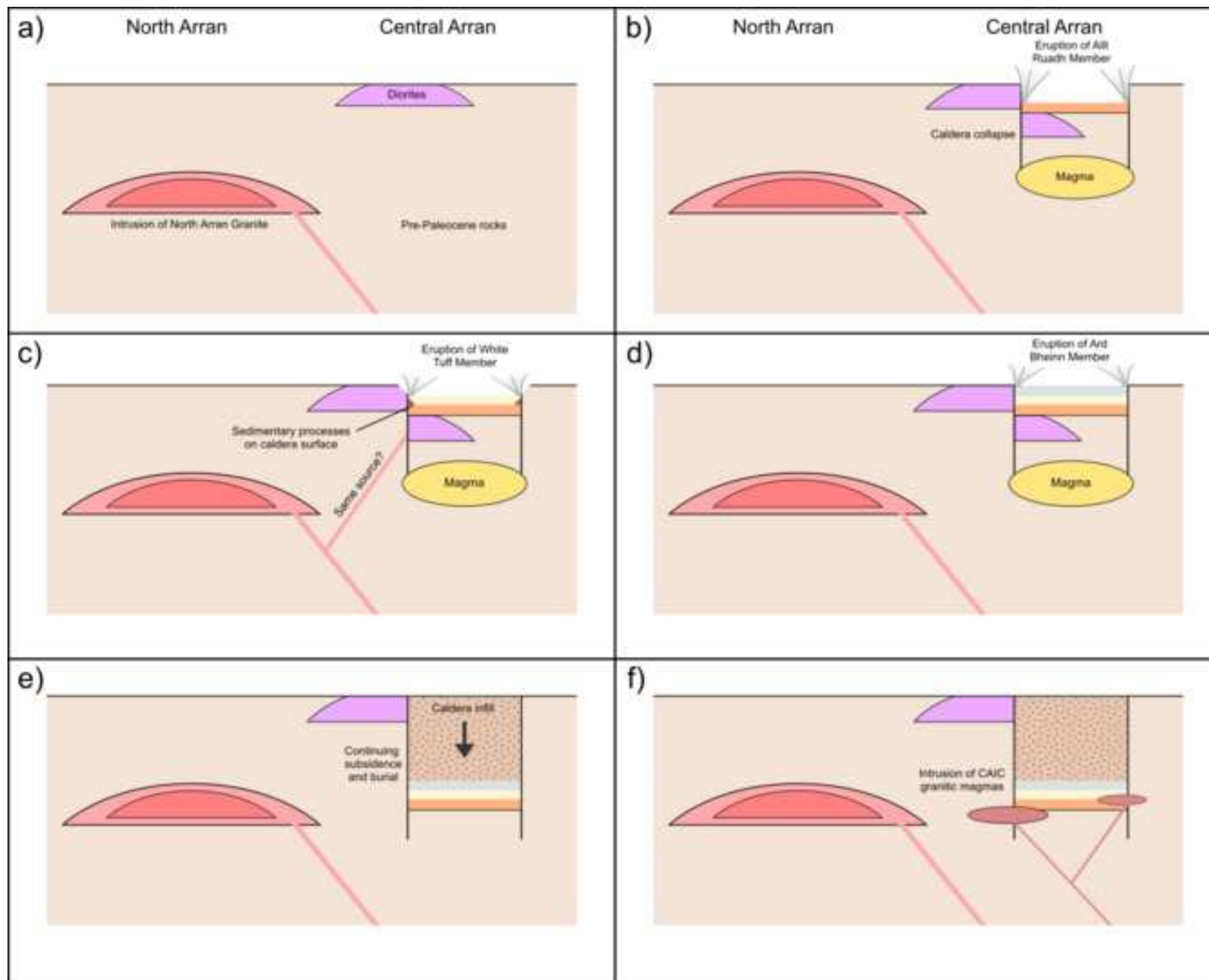
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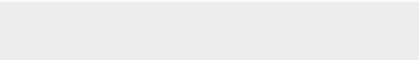


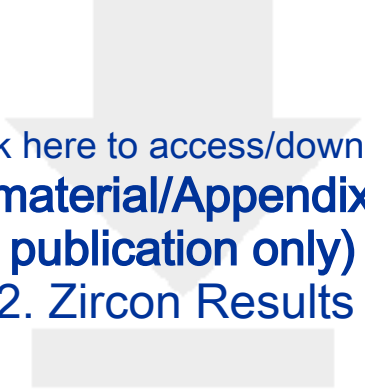


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**Supplementary material/Appendix (Files for online
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Appendix 1. Zircon methods.docx

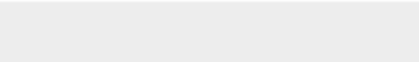
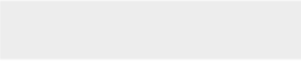




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**Supplementary material/Appendix (Files for online
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Appendix 2. Zircon Results Table.xlsx





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Appendix 3. Representative CL images.docx

