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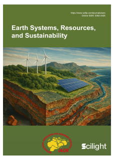

Article

Episodic Vertical Movements of Supposedly Stable Cratons

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ABSTRACT

Cratons are generally held to be stable, but stability means different things to different specialities. A key characteristic of cratons is the scarcity of cover rocks on Precambrian basement. This property has led many to assume—explicitly or indirectly—that the gap in the stratigraphic record represented by the lack of Phanerozoic cover implies tectonic stability over millions of years. Here we show that supposedly stable cratons have experienced multiple episodes of subsidence and uplift at the scale of kilometres, involving deposition and removal of sedimentary covers. These episodes affect regions at a continental scale, including cratons as well as continental margins. We present a series of case studies based on observations of regional landscapes in relation to stratigraphic constraints and thermal histories derived from apatite fission-track analysis. Evidence of former covers is commonly dismissed as unrealistic, but evidence of vertical movements of cratons has been known for decades, so we question why this is not widely accepted. Some may consider km-scale movements to be insignificant or choose to assume stability based on conventional thinking, while others dismiss the evidence due to the lack of an accepted mechanism by which such covers could have been deposited and removed. To counter that argument, we suggest a variety of lithospheric and sub-lithospheric processes that may explain the observations presented here. It is time to reject the paradigm of cratonic stability and accept that cratons have undergone positive and negative, km-scale vertical motions over geological timescales.

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Research Highlights

- Supposedly stable cratons have experienced multiple episodes of subsidence and uplift, involving deposition and removal of km-thick sedimentary covers.
- These episodes affected regions at a continental scale, including cratons as well as continental margins.
- It is time to reject the paradigm of cratonic stability.

1. Introduction

The term craton was applied by Hans Stille [1, 2]—during the times preceding plate tectonics—in the sense of a strong unyielding shield [3]. In those days, cratons were seen as bounded by geosynclines, but whereas the concept of geosynclines was superseded by the advent of plate tectonics (and replaced by rifted and active margins), the term craton has survived to the present day. The first paper published with the word craton in its title appeared in 1947 (according to webofscience.com), and the number of such papers has increased through time, reaching 532 in 2025. Therefore, it is important to understand the meaning of the term craton and to study the behaviour of these major geological entities over geological time.

A key characteristic of cratons is the scarcity of Phanerozoic cover rocks on Precambrian crystalline basement. This property has led many to assume—explicitly or indirectly—that the gap in the stratigraphic record represented by the lack of cover implies tectonic stability over millions of years during which cratons undergo only slow and more or less continual denudation and emergence [4–13].

In a recent review, Pearson et al. [14] defined cratons as coherent blocks of Precambrian lithosphere, for which lithosphere as well as crust are typically stable for time periods in excess of a billion years owing to protection by deep (>150 km) lithospheric keels. They noted that this definition was a pragmatic generalization, and that cratons and their roots are periodically disrupted by rifting and invasion by magmatic products. This reflects a broader definition of a craton as a segment of continental crust that has attained and maintained long-term stability, with tectonic reworking being confined to its margins [15]. Larger composite cratons may consist of Archean nuclei surrounded by Paleoproterozoic to Mesoproterozoic crust, all underpinned by thick cool lithospheric mantle. Pearson et al. [14] defined supercratons as comprising multiple composite cratons (Figure 1).

A thick lithospheric mantle is a distinguishing feature of cratons, linked to their stability [14]. These deep strong mantle keels thus appear to play a part in protecting the overlying crust from reworking and recycling, diverting mantle plume heat and mass fluxes away from the roots without much modification, unless weakened by metasomatism.

Hawkesworth et al. [16] among others also argued that cratons are areas of stable continental lithosphere. But while the stability of cratons in terms of the great age of their lithospheric keels is widely accepted, it is often less clear just what the term 'stability' implies, particularly in terms of possible vertical movements of the bedrock surface of cratonic regions. Burgess [17] presented a pragmatic view that the craton in North America was an area underlain by Precambrian basement that had not been subject to plate-margin processes during the Phanerozoic but stressed that epeirogeny had affected the cratonic interior. He found it surprising that the Phanerozoic history of the craton is often viewed as, per definition, 'tectonically stable'. More recently, Shirmard et al. [18] discovered that mineralized craton edges consistently cluster 800–1800 km from subduction zones at the time of formation and concluded that subduction near cratons fosters conditions that enrich the mantle and promote mineral formation along craton edges.

Some cratons preserve Phanerozoic sedimentary covers, varying from thin remnant outliers to km-thick sedimentary basins, showing that cratonic crust can undergo subsidence (and burial), while some provide evidence revealing uplift (and exhumation). Sloss [19] reviewed the Phanerozoic cover of the North American Craton, pointing out that *'Interregional unconformities are virtually craton wide, traceable to variable distances outboard from cratonic interiors to continental shelf prisms and are not confined to specific portions of cratons'*. Speculating on the magnitude of the vertical amplitude of uplift associated with such unconformities, Sloss [19] commented that while '*many cratonic unconformities … suggest vertical uplift and concomitant erosion of a few hundred metres, … within the range of sea level rise and fall,* (others of similar scope) *are, however, difficult to resolve without consideration of a kilometer of more of uplift and erosion*'. Kohn and Gleadow [20] provided an extensive review of evidence from low-temperature thermochronology (LTT) for exhumation of cratonic regions in which kilometre-scale thicknesses of rock have been removed. Such studies generally assume that the rock removed during exhumation was the same as what is preserved—i.e. more basement, but as we will show, evidence suggests a more complex history.

This evidence of positive and negative vertical movements conflicts with the concept of cratonic stability and is still resisted by many (see discussion in later sections regarding contradictory views). In general, discussion of craton development has been dominated by simplistic ideas assuming vertical stability.

One obstacle to understanding is that stability means different things to those with different specialities. To geochemists and geophysicists, who work in terms of lithospheric thicknesses of 100s of km and timescales of 100s of Myr, events involving a few kilometres of exhumation may be insignificant, but to those geoscientists concerned with the development of the surface of the earth, such magnitudes are of key importance. When attitudes from the former are transposed to the latter, problems can arise if 'stability' is interpreted as meaning that vertical motions leading to deposition and removal of several kilometres of cover are not possible on a stable craton. Despite the comments quoted above, Sloss [3] discussed '*maintenance over millions to 10s of millions of years of the solid surfaces of cratonic lithosphere within tens of meters (or at most one or two hundred meters) of sea level'*. He further suggested that for '*extraordinary spans of geologic time'* uplift and subsidence of cratonic terranes rarely exceeded the rates of erosion and sedimentation, respectively.

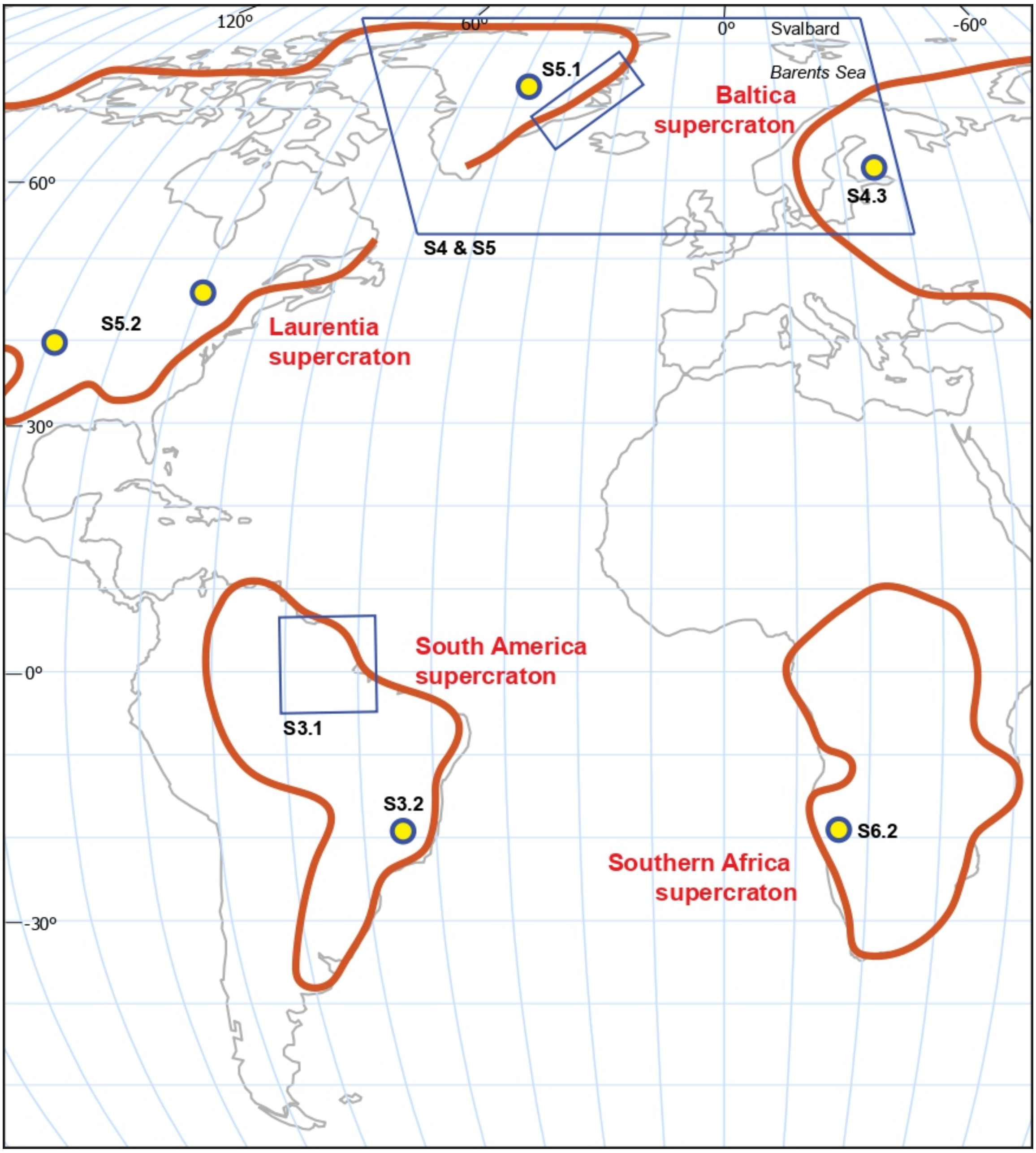

Figure 1. Outline of supercratons along the Atlantic Ocean (modified after [14]). Location of cases discussed here are indicated. The map shows the outline of the South American and southern Africa supercraton as well as parts of the Laurentia and Baltica supercratons. The remaining supercratons, not shown, are the Antarctica and Australian supercratons. The definition of cratonic regions is based on seismic imaging of continental mantle lithosphere defining regions of deep lithospheric keels. Composite cratons comprise multiple Archean nuclei/cratons and the six supercratons comprise multiple composite cratons. The annotations refer to the sections where the cases are discussed: S3.1: Guiana Shield. S3.2: São Francisco craton. S4.3: Baltica. S4+S5: Greenland and Fennoscandia. S5.1: East and Central Greenland. S5.2: North American craton. S6.2: Namibia.

It is therefore important to understand the vertical motion of cratons in detail, and to do so it is necessary to decipher the gap in the stratigraphic record represented by the basement surface. Ager [21] was one of the few geologists to emphasise the importance of gaps in the stratigraphic record, coining the phrase "*the gap is more important than the record*". Our approach is to integrate the preserved geological record (particularly sedimentary outliers) with evidence of missing section, i.e. rocks which were once present but have subsequently been removed [22]. This approach has provided clear evidence that many basement regions, both cratonic and others, have undergone multiple episodes of both subsidence and uplift throughout the Phanerozoic, in which kilometre-scale thicknesses have been deposited and removed, often leaving only minor remnants, if any, in the preserved geological record [22]. Such vertical motions can be recognized from stratigraphic information [17, 19], landscape studies [23–25] and thermochronology [20].

Here we provide examples from cratonic regions of multiple positive and negative kilometre-scale vertical movements, showing that cratons are far from stable on such scales. We present a series of case studies based on a combination of observations of the large-scale landscape in relation to stratigraphic constraints, stratigraphic landscape analysis (SLA) [26] and thermal histories derived from apatite fission-track analysis (AFTA) data [27]. These examples are taken from the studies that we have conducted in Baltica and Laurentia (including Greenland) as well as the South American supercraton (as defined by [14]) (Figure 1). The documentation of km-scale vertical movements, involving burial and exhumation of cratons, has profound implications for our understanding, not only of the properties of cratons but also of the properties of the deep earth.

In the following, we describe the techniques used in defining vertical movements and missing section before we review examples of episodic burial and exhumation in cratonic regions. We then consider the question of why such movements have not been widely recognised in previous studies and finally suggest some possible mechanisms to explain these observations.

2. Methods

2.1. Timing and Magnitude of Exhumation from Low-Temperature Thermochronology

In the temperature range appropriate to the study of kilometre-scale denudation, two techniques of LTT are in common use, viz. apatite fission track (AFT) and apatite (U-Th-Sm)/He (AHe). Thermal history information derived from these methods at paleotemperatures up to $\sim$120 °C can constrain the timing of major phases of exhumation (cooling) and can be converted to former depths of burial and hence amounts of section removed during exhumation. Analysis of samples over a vertical interval allows determination of paleogeothermal gradient, allowing greater precision in estimation of removed thickness.

Over the last 40 years or more, LTT has been widely applied to study denudation of cratons, continental margins and other basement regions, as well as outcropping plutons [28]. In the absence of cover rocks, LTT represents one of few approaches for unravelling the denudation history of basement regions in quantitative terms.

2.1.1. Continuous Cooling vs. Stratigraphic Constraints

LTT studies of basement regions are commonly carried out with the aim of defining the complete history from the onset of daughter product retention (fission tracks or helium) to the present day, usually assuming a framework of slow, continuous cooling. This approach is based on the concept that such regions are buoyant, undergoing progressive emergence as they are denuded, through isostacy. On this basis, cooling rates from LTT can be converted to rates of exhumation, over timeframes of 10s or 100s of Myr.

Despite the power of LTT methods, results have often conflicted with more conventional investigations based, for example, on stratigraphic reconstructions and regional geological trends [29]. A significant cause of this conflict arises from a basic limitation of conventional approaches based on the assumption of continuous cooling, since LTT methods can only detect times when a sample cooled from higher temperatures, and are insensitive to times when samples were cooler [30]. If a sample cools and is then reheated to a higher temperature, all evidence of the period at lower temperatures is overprinted [27, 29]. Thus, using this conventional approach for a sample covered by one or more sedimentary units cannot independently reveal times at which a sample was exhumed to the surface prior to reburial (Figure 2A).

This conflict can be resolved by taking into account basic geological constraints when converting LTT data to thermal histories [29]. Where sedimentary cover units overlie basement, stratigraphic details provide important information on when the underlying basement surface was at the surface. Unfortunately, a number of studies have failed to take note of such basic constraints, resulting in misleading and inaccurate histories [22, 29].

2.1.2. Episodic Heating and Cooling

To reconcile LTT results with other observations, it is important that thermal history information is extracted from the data in a manner that does not conflict with geological evidence. We have previously made the case that histories involving slow, continuous cooling are not appropriate, instead advocating that LTT data should be interpreted in terms of histories involving episodic heating and cooling, reflecting burial and exhumation [30]. This conclusion is based on a variety of evidence, but primarily on the observation that in many regions, integration of LTT data with simple geological observations—such as the age of cover units overlying basement and well-dated erosion surfaces—demonstrates such histories [22]. It seems reasonable to conclude that if such behaviour is demonstrated in areas where cover remnants are present, then other areas where cover is absent should behave in similar fashion.

Therefore, in our own studies we use an approach which we refer to as AFTA (apatite fission-track analysis), in which we do not attempt to define the complete history, but focus on those aspects that are encoded in the data (i.e. times at which a sample began to cool from higher temperatures). We assume a framework of episodic heating and cooling. Where sedimentary deposits or well dated erosion surfaces are present, these can be used to provide direct constraints on surface exposure (Figure 2B), otherwise we assume heating and cooling rates of 1 °C/Myr and 10 °C/Myr, respectively (Figure 2C).

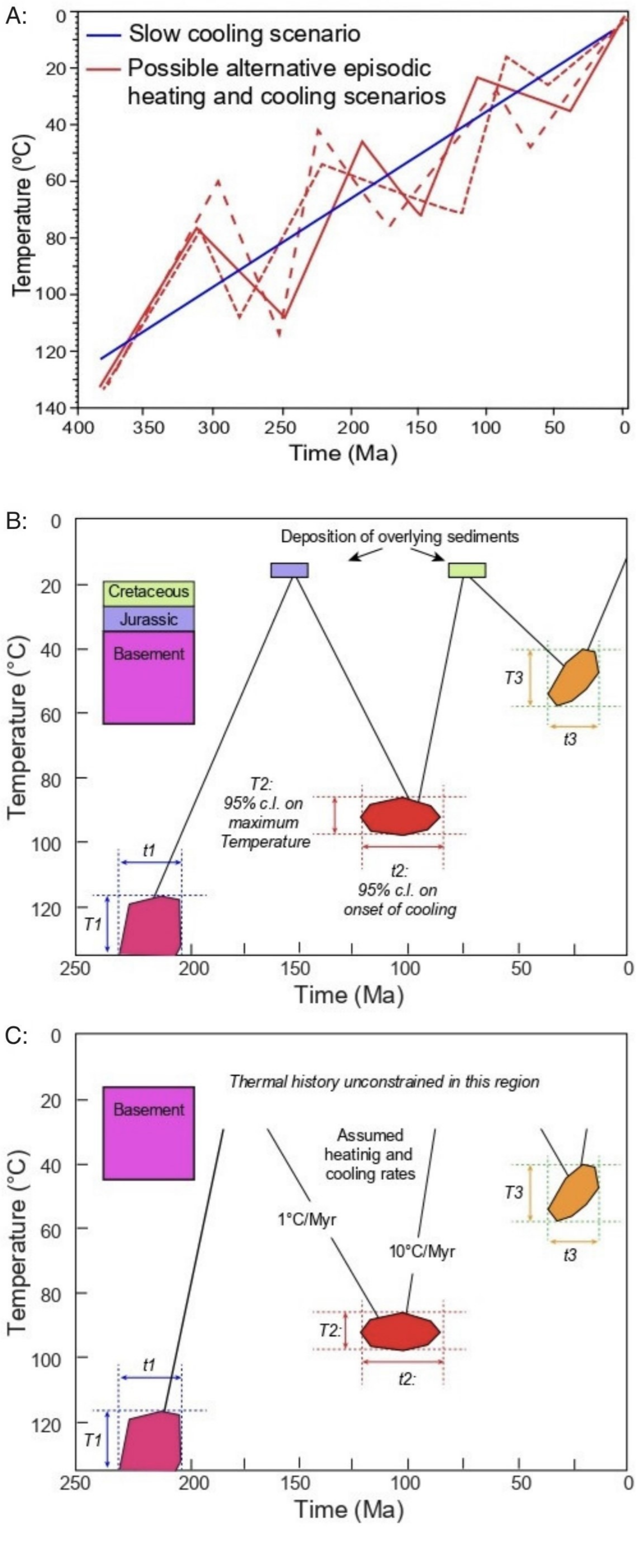

Figure 2. Interpretation of apatite fission-track data. (**A**) Monotonic vs. episodic cooling histories. Apatite fission-track (AFT) data only contain information on periods when the sample cooled from higher to lower temperatures, so data alone cannot discriminate between a continuous cooling history (blue) and alternative histories involving episodic burial and exhumation (red). (**B**) Where basement is overlain by sedimentary units, these provide key geological constraints on possible solutions, allowing determination of the timing and magnitude of key paleo-thermal episodes. Coloured areas represent 95% confidence intervals on the time at which cooling begins (*t1*, *t2*, *t3*) and the maximum/peak paleotemperature (*T1*, *T2*, *T3*). For full details see Green and Duddy [30]. (**C**) A large number of studies have led us to conclude that histories as shown in B represent the most appropriate scenario for extracting thermal history information from AFT data [22]. For basement samples where no cover is present, we assume heating rates of 1 °C/Myr and cooling at 10 °C/Myr, as shown.

In the following, we will present evidence from LTT studies to show that episodic vertical movements provide a geologically more realistic framework for interpreting LTT data, even in cratonic regions, and that adherence to the outmoded concept of slow, continuous cooling provides misleading outcomes.

2.1.3. Misconceptions Regarding the Partial Annealing Zone

Certain aspects of LTT data, such as a broad spread in track lengths or a scatter of AHe ages are often attributed to prolonged residence in the partial annealing zone (for AFT) or partial retention zone (for Ahe), referring to the temperature ranges where tracks or He are only partially retained. Such phrases illustrate the preference for slow cooling scenarios in interpreting LTT data, but as emphasised by [27], similar effects can be produced by reheating into the appropriate temperature range.

2.2. Relative Denudation Chronology from Stratigraphic Landscape Analysis

Following the definition of Pearson et al. [14] that cratons are coherent blocks of Precambrian lithosphere, it is clear that the surface of the cratons are erosion surfaces because the Precambrian basement rocks were formed at great depth and at high temperature. Thus, by definition, cratons have a history of deep exhumation.

In many parts of the world cratons are characterized by low relief surfaces of regional extent. Here we will highlight some of the general aspects of the formation and preservation of erosion surfaces, how these concepts have developed over time, and how analysis of landscapes constrained by stratigraphic observations can provide evidence of vertical movements through time.

2.2.1. Landscapes in Steps; Flat and Hilly Peneplains

Different erosional processes may lead to the formation of low-relief surfaces of regional extent, and this has led to multiple terms describing erosion surfaces. Davis [31] attributed the final phase of the fluvial erosional cycle down to sea level (involving the decline of slopes) as responsible for creation of vast low-relief surfaces, which he termed peneplains. This concept explains the limited influence of geological structure on the landscape in long-time perspective, even in landscapes being formed at the present (Figure 3A). It is worth noting that fluvial erosion becomes less effective in the lower part of the system, but this occurs during the final formation of the peneplain. Any rock that is above base level will erode by other processes e.g. weathering, and the fluvial system will transport the debris.

However, the model of Davis cannot explain the presence of plateaus separated by escarpments (stepped landscapes). King [23, 32] also regarded slope retreat as important for surface formation, but unlike Davis [31], King observed that escarpments underwent parallel retreat rather than decline, and he thus regarded valley incision as responsible for surface formation (pediplanation) governed by the base level (cf. the observations presented by [33]). The implication of this interpretation is that peneplains in stepped sequences are markers of former base levels, and thus that the steps define former uplift events (Figure 3B). Many researchers—before and after King—have followed this interpretation of the landscape [34–39].

Apart for fluvial processes, erosion surfaces may form during warm and humid climates by deep weathering of basement rocks, leading to formation of a weathering front and subsequent removal of the weathering products (stripping) [40–43]. Water from warm rain may seep into fractures and transform the feldspars in granitic rocks into clays, resulting in the formation of a saprolite (a 'rotten rock'). The areas of basement rocks between the fracture zones is much less affected by the weathering processes, and subsequent erosion washes some of the clays out of the fracture zones, leaving fracture valleys and rounded hills (typically 200 m high) formed where fracture valleys intersect (hilly relief). The end result is thus a low-relief surface with scattered hills (Figure 3B) governed by the base level during the formation of the surface [44].

In summary all erosional surfaces graded to former base level should be considered as peneplains—whether the local topography is hilly or flat—because removal of the erosional products eventually will be transported to the sea by fluvial processes [29, 37].

2.2.2. Burial, Preservation and Re-exposure of Peneplains

Presence of marine cover rocks demonstrate that sea level acted as base level for the formation of extensive peneplains in many cases; for example, the Sub-Cambrian Peneplain in the western Baltic Shield was flooded by shallow seas during the Cambrian and Ordovician [45]. Also on the Baltic Shield, in south-western Sweden, remnants of Upper Cretaceous marine sediments rest on the mid-Cretaceous peneplain [26]. These observations also show that a peneplain may be buried after its formation and consequently, be preserved below a sedimentary cover. Eventually, the cover may be removed during exhumation and the underlying basement surface re-exposed.

Multiple episodes of uplift (and peneplain formation) followed by subsidence (and burial of the peneplain below a protective cover) may lead to re-exposure of the older peneplain in some places and its destruction elsewhere. Therefore, older peneplains are less likely to be preserved to the present day; e.g. in Greenland and North-East Brazil where the landscapes are dominated by Cenozoic peneplains [24, 46, 47]. In Sweden and Finland, the widespread Sub-Cambrian Peneplain is a notable exception [26, 48], while this surface occurs in places as a well-defined unconformity where the peneplain remains buried beneath Cambrian sedimentary cover. Evidence of other episodes of exhumation across the Baltic Shield are only preserved as unconformities in remnants of the sedimentary cover. The preservation of older peneplains to the present day thus depends on the balance between the competing magnitudes of exhumation and burial over time. Note also that peneplains also may extent across sedimentary covers, and that therefore those parts of peneplains are less likely to survive to the present day.

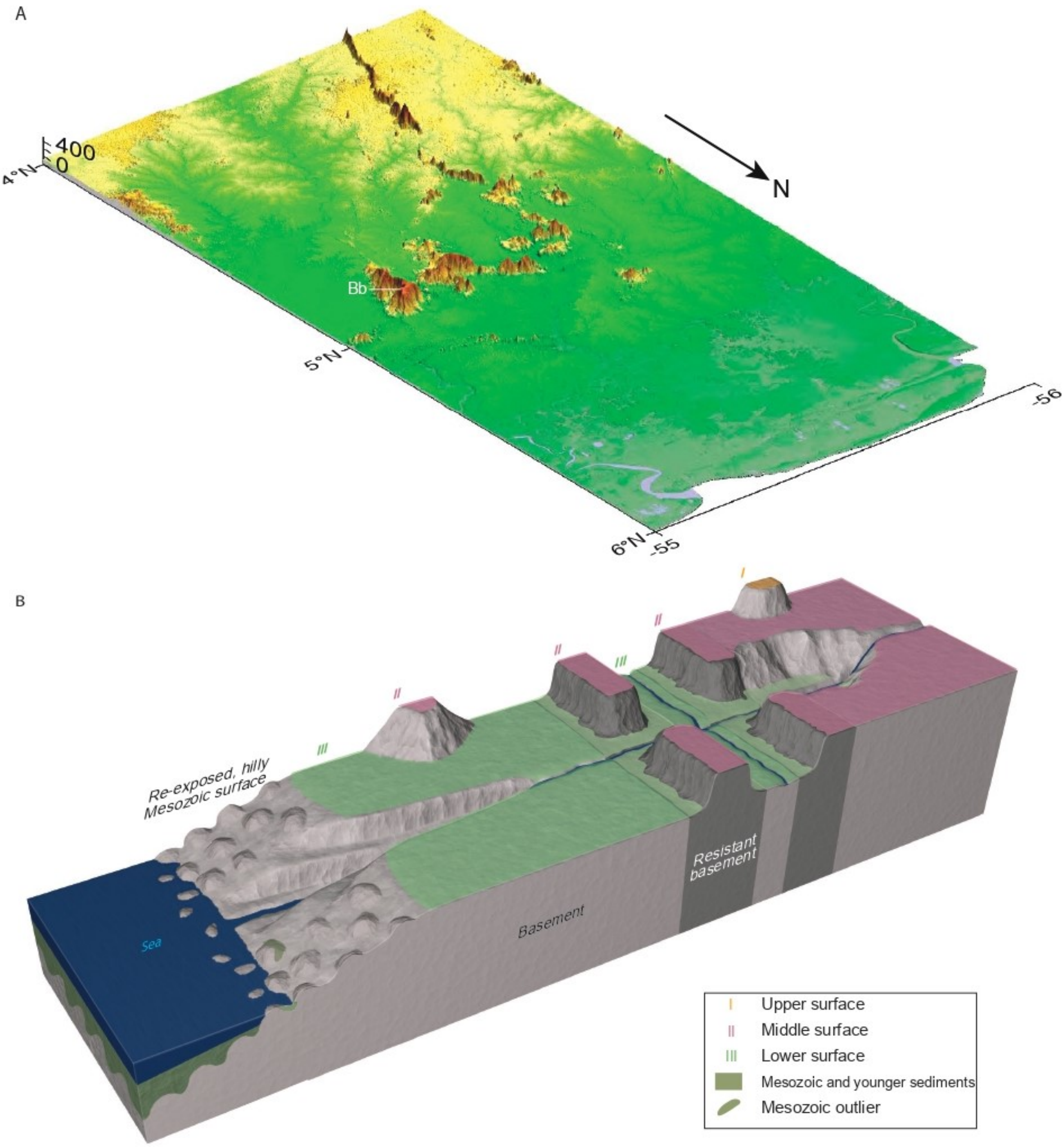

Figure 3. Peneplains graded to sea level and subsequently uplifted. (**A**) The Atlantic Guiana Surface graded to sea level since the late Miocene cuts across basement and the sediments of the coastal zone of Suriname [49]. It rises from sea level to about 200 m inland around 300 km from the coast. Residual mountains rise above the surface such as the bauxite-capped Brownsberg (Bb) and the elongated ridge that corresponds to Precambrian doleritic dykes [50]. Elevation in meters. (**B**) Generalized model of relief development based on landscape analysis of southern Scandinavia (modified after [29, 37]). The near-horizontal peneplain III cuts off a re-exposed and inclined sub-Mesozoic peneplain with hilly relief. This configuration can be explained by the following sequence of events: (1) Formation of the Mesozoic peneplain by erosion to sea level by weathering during warm and humid climate. (2) Accumulation of a protective cover of Mesozoic and possibly younger sediments above the peneplain. (3) Tilting of the Mesozoic peneplain. (4) Formation of peneplain III after Miocene exhumation by river erosion to sea level extending across basement and (now missing) sedimentary cover. (5) Pliocene uplift of the region leading to removal of most of the protective cover above the Mesozoic peneplain. The remnants of the more elevated peneplains I and II, represent older erosion surfaces.In the case of the Southern Scandes, the Mesozoic cover rocks are of Late Jurassic age, in the case of the South Swedish Dome, the cover rocks are Late Cretaceous in age.

2.2.3. Stratigraphic Landscape Analysis

Classical models of landscape development focus on the idea of continuous uplift, interrupted by periods of quiescence [23, 31]. However, stratigraphic landscape analysis; SLA [26] is based on: (1) The relationship between relief in basement and cover rocks provides information about both uplift and subsidence of a region. (2) The crosscutting relationships between peneplains of different tilts and with different relief and saprolite remnants (Figure 3). (3) The occurrence of valleys incised below peneplains indicating the uplift history of the peneplain since its formation as an erosion surface graded to base level. The subsequent widening of the incised valley near base level eventually results in a valley-in-valley pattern [51, 52] and a regional landscape characterized by stepped surfaces. (4) Finally unconformities in sedimentary basins can often be correlated with the formation of peneplains [53, 54]. These observations provide information about the relative denudation chronology, a key input to the study of the vertical movements of basement terrains.

3. The South American Supercraton

3.1. The Guiana Shield

The Guiana Shield is the northern part of the Amazonian Craton, separated from its southern counterpart, the Brazilian Shield by the Amazon–Solimões basin [55–57]. Proterozoic rocks dominate the Guiana Shield, so it might be expected to be an example of geological stability over Phanerozoic time. However, the stratigraphic record along the flanks of the shield provides evidence of a complex history which is difficult to reconcile with Phanerozoic stability: Cretaceous sediments rest on basement on the northern flank of the shield, while a Paleozoic cover is present on the southern flank (Figure 4D). The Paleozoic sediments of the Amazon Basin thin towards the shield areas to the north and south of the basin and are progressively truncated in these directions [58, 59]. A base-Cretaceous unconformity separates the Paleozoic sediments from Cretaceous and Paleogene sediments, but Triassic and Jurassic sediments are absent (Figure 5) [60]. Along the coast of Suriname, significant unconformities occur in the Late Cretaceous—Cenozoic succession [61, 62].

Furthermore, several studies have identified a number of planation surfaces at different elevations across the Guiana Shield, all reaching the conclusion that the surfaces below the summits were formed during the Cenozoic [63, 64]; a conclusion that contradicts the supposed cratonic stability.

Despite these simple observations, the Guiana Shield is widely regarded as a craton in classical geological terminology and has thus often been assumed to be relatively stable through the Phanerozoic, undergoing slow denudation and emergence while major tectonic events occurred at the margins of the Amazonian Craton [11, 12, 57]. Thermochronological studies of the shields north and south of the Amazon River have been interpreted as supporting this scenario [65–68].

These previous studies paid no regard to the possibility that Phanerozoic covers had accumulated and subsequently been removed across the shield, which would indicate both subsidence and uplift movements across the supposedly stable basement terrain. To investigate this possibility, we conducted a study integrating AFTA data with observations of the large-scale landscape and the stratigraphic record [49]. A key objective of the study was to combine results from the Guiana Shield (east of 60° W, which we will refer to as the Guiana Shield) with results from the Amazon Basin in the south and Guyanas margin in the north.

3.1.1. Episodes of Exhumation: Guiana

AFTA data from the Guiana Shield and surrounding sedimentary basins reveal four dominant regional cooling episodes (Figure 5), viz. earliest Jurassic ('CAMP'), Valanginian–Hauterivian ('Neocomian'), latest Aptian—mid-Albian ('Albian') and Eocene (names in quotes are a short-hand for reference).

'CAMP' indicates cooling following the CAMP intrusive event, part of the Central Atlantic Magmatic Province; c. 201 Ma [69]. CAMP intrusions transect the basement rocks of the Guiana Shield and the Paleozoic sediments in the Amazon Basin [56, 60, 70].

Except for the Albian episode, these episodes are recognised over a wide region including the Guiana and Brazilian shields and the Amazon Basin. The Albian episode is only recognized in a restricted area of the Guiana Shield where Neocomian paleotemperatures were sufficiently high to overprint the CAMP episode, although it sems likely that Albian exhumation was also regional in extent. Evidence for Eocene cooling is also resolved in samples from an offshore well in the Casiporé Basin.

Other post-Paleozoic cooling events were resolved in restricted locations, beginning in the following intervals, viz: Campanian–Maastrichtian, late Paleocene—earliest Eocene ('late Paleocene') and Miocene.

In the shield areas proper, where Phanerozoic sedimentary cover is absent, the AFTA results cannot be directly used to discriminate between a history of progressive, continual cooling and one of episodic burial and exhumation. However, integration of AFTA data with regional geological constraints provides insights into the vertical movements of this supposedly stable craton.

Neocomian paleotemperatures are similar in outcrop samples of both basement rocks around the basin margins and Paleozoic sediments within the Amazon Basin (Figure 6A). Results from Amazon Basin well 1-SP-1-PA show that the Neocomian paleotemperatures reflect deeper burial by c. 3 km of Permian to lowermost Cretaceous sediments, subsequently removed by exhumation resulting in the major base-Cretaceous unconformity in the Amazon Basin. Results from outcropping Paleozoic sediments on the northern and southern flank of the Amazon Basin also define cooling from peak paleotemperatures around 100 °C prior to Neocomian cooling, equivalent to burial below several kilometres of Paleozoic to lowermost Cretaceous sediments (Figure 7A).

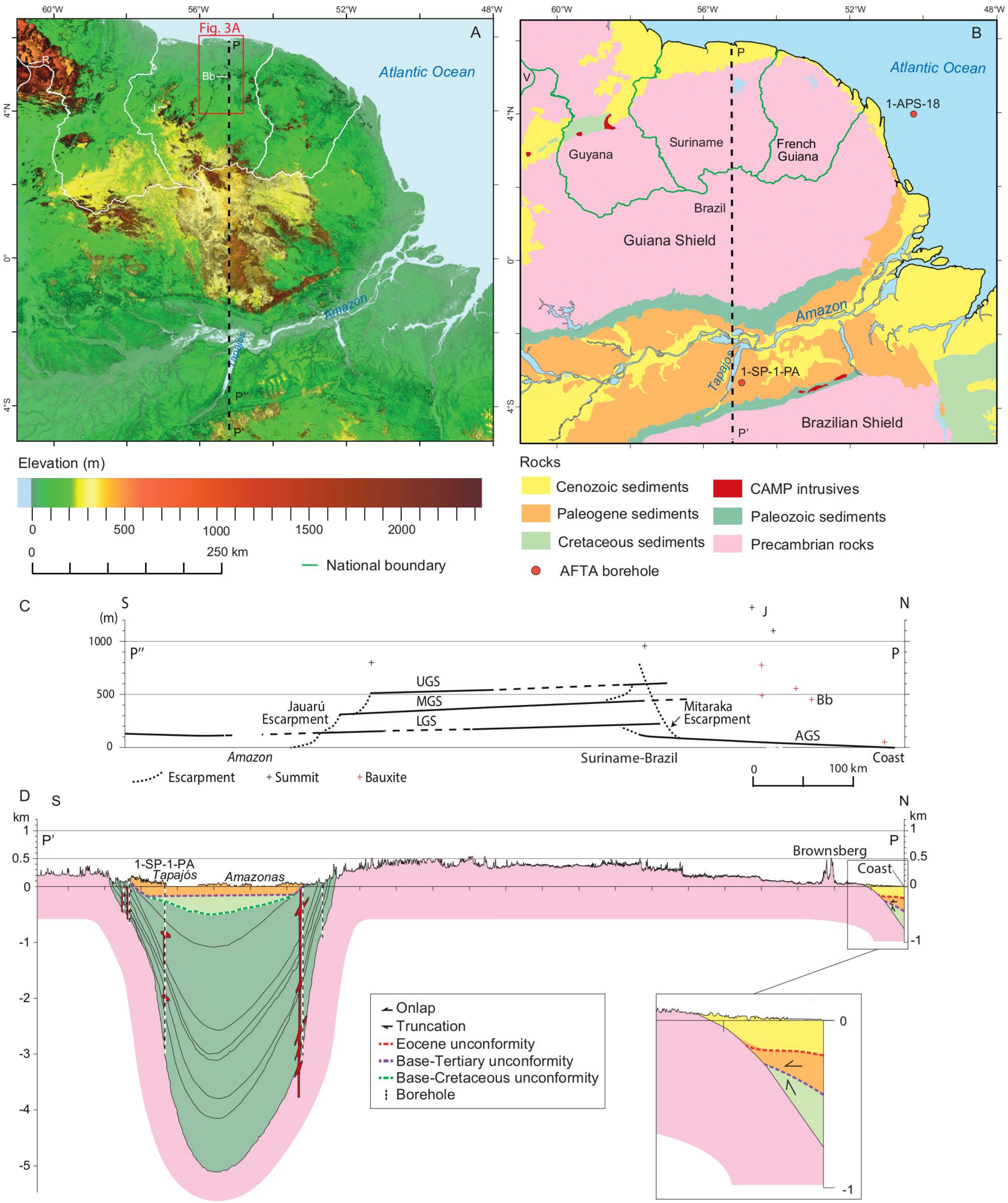

Figure 4. Topography and geology of the eastern Guiana Shield and the Amazon Basin (modified after [49]). (**A**) Elevation. Highest summits in the eastern and the western part of the shield. J: Julianatop (1280 m a.s.l.), R: Mount Roraima (2810 m a.s.l.), Bb: Brownsberg (515 m a.s.l.). (**B**) Geology and well locations. V: Venezuela. (**C**) Generalized profile illustrating the relation between planation surfaces and escarpments along the profile PP′′ in (**A**). The high-level surfaces are tilted towards the south, while the Atlantic Guiana Surface (AGS) is graded towards the base-level of the Atlantic Ocean in the north (see 3D image in Figure 3A). (**D**) Geology and elevation across the Guiana Shield and the Amazon Basin along transect PP′ in (**B**). AGS/LGS/MGS/UGS: Atlantic/Lower/Middle/Upper Guiana Surface.

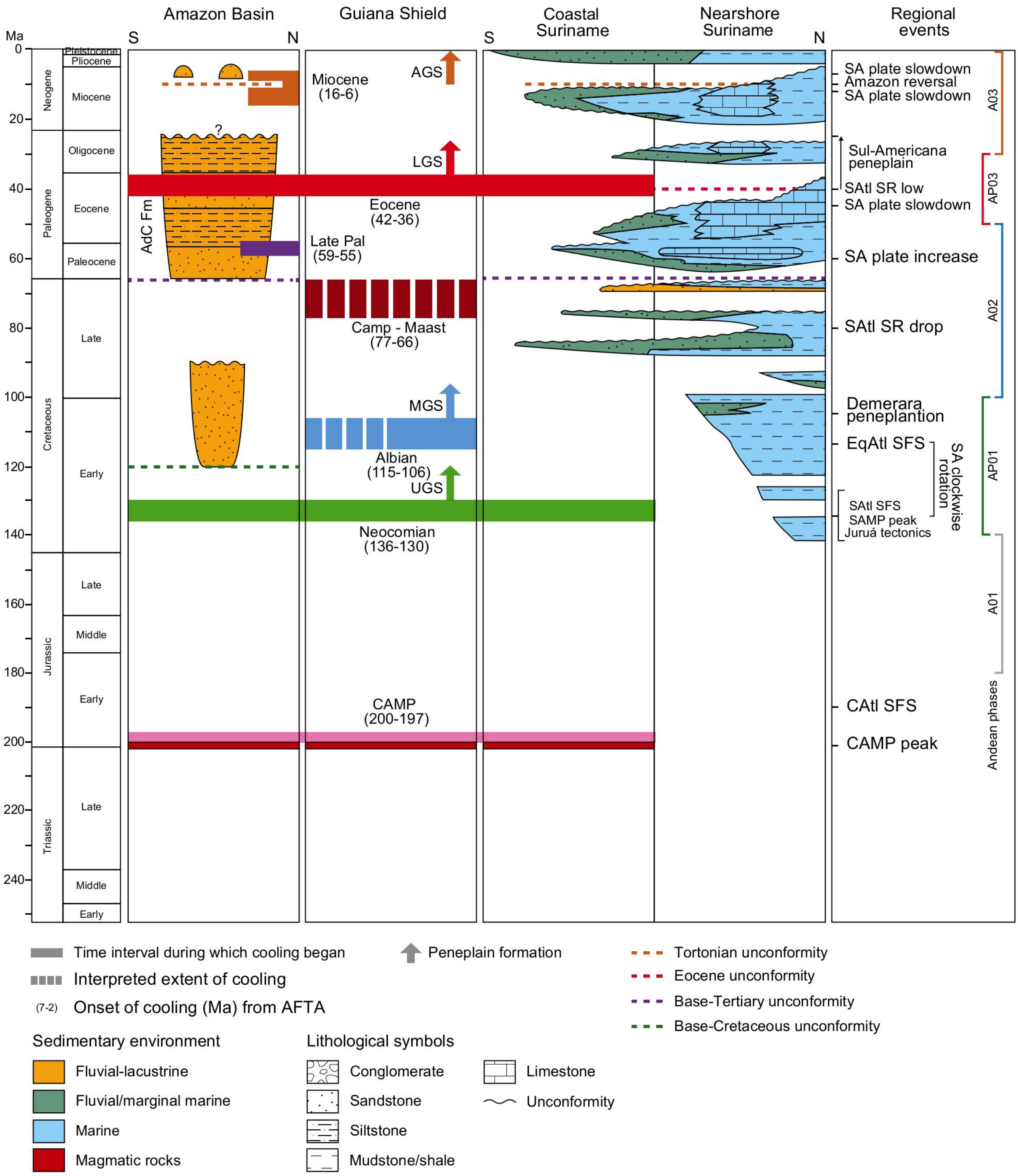

Figure 5. Mesozoic–Cenozoic stratigraphy compared with the onset of cooling episodes defined from AFTA for the Guiana Shield and adjacent basins and time intervals for peneplain formation [49]. The vertical extent of the horizontal, coloured bars indicates the uncertainty in the onset timing of the cooling episode. The two events shown as stippled in the Guiana Shield column are recognised in the pre-depositional history of apatite grains in sandstones and are interpreted as representing exhumation episodes in regions that have not yet been detected by sampling. The continental sandstones and conglomerates of the Paleogene Alter do Chão Fm (AdC Fm) are difficult to date, so we suggest that the Eocene exhumation defines an Eocene age for the youngest part of the Alter do Chão Fm. Regional events after Japsen et al. [49] based on [71–77]. CAMP: Central Atlantic Magmatic Province. CAtl: Central Atlantic. EqAtl: Equatorial Atlantic. SA: South America. SAMP: South Atlantic Magmatic Province. SAtl: South Atlantic. SFS: seafloor spreading. SR: spreading rate. AO1–AO3: Andean Orogeny phases 1–3 and APO1–APO2: Andean post-orogenic phases 1–2. UGS, MGS, LGS and AGS: Upper, middle, lower and Atlantic Guiana surfaces.

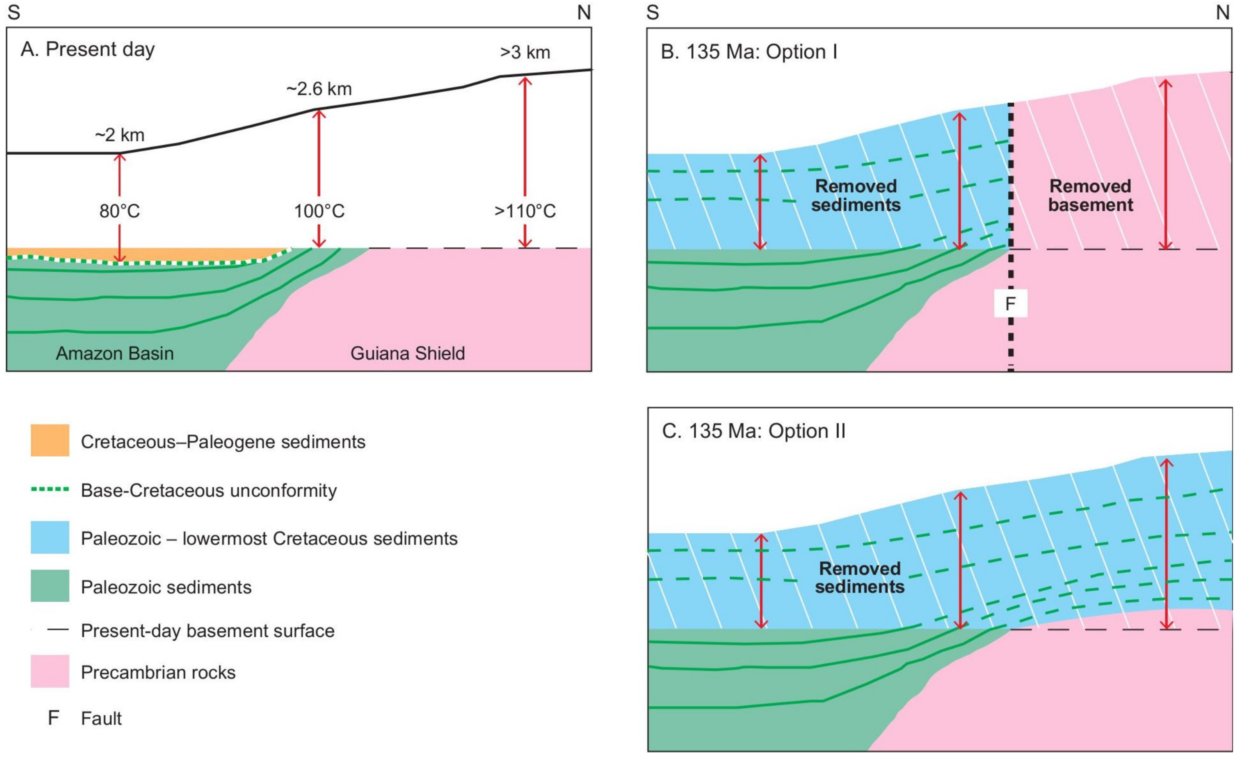

Figure 6. Conceptual illustration of possible explanations of Neocomian paleotemperatures (at c. 135 Ma) across the Guiana Shield and Amazon Basin [49]. (**A**) Observed Neocomian paleotemperatures. (**B**) Option I: At outcrops across the shield, additional rock thickness required to attain paleotemperatures prior to the onset of Neocomian exhumation was basement rock, whereas in the basin heating was due to additional sedimentary units. (**C**) Option II: Neocomian paleotemperatures across the whole region were the result of burial below a sedimentary cover (with a possible contribution of an additional thickness of basement in the shield, eroded during subsequent exhumation). Option I represents the conventional interpretation of low- temperature thermochronology data in basement regions, where cooling is interpreted as representing progressive emergence of a cratonic region. This requires a major structure separating basin from basement, as indicated by fault F, but no such structure is known [58, 59]. Option II represents an alternative interpretation, which is consistent with the progressive truncation of the Paleozoic strata towards the shield and with the continuity of cooling from basin to basement. This scenario implies a history of episodic burial and exhumation for both basin and basement. The figure is based on a paleo-geothermal gradient of 30 °C/km and a surface temperature of 20 °C.

If data from outcropping shield samples reflect a history of slow, continuous cooling, as commonly assumed to be appropriate for the Guiana Shield, then the rock column removed during cooling must have been additional basement. This is difficult to reconcile with the clear evidence that synchronous cooling in the basin represents removal of a thick sedimentary pile, as it would require a major vertical offset between basin and shield (Figure 6B). However, no such structure is known [59, 78]. Since Neocomian exhumation is regional and synchronous in both the Amazon Basin and in the Guiana Shield, the evidence leads to the conclusion that the preceding burial phases recorded in the basin must also have affected the shield (Figure 6C). A similar conclusion applies to the Eocene episode, which is also detected in basin and shield.

3.1.2. Peneplains: Guiana

Our study identified four regional planation surfaces across the Guiana Shield based on topographic maps and profiles (Figure 4C):

1. **The Upper Guiana Surface** (UGS) in the central part of the shield; 450–600 m above sea level (a.s.l.).
2. **The Middle Guiana Surface** (MGS) around the central part of the shield; 350–500 m a.s.l.
3. **The Lower Guiana Surface** (LGS) across the Paleogene sediments of the Alter do Chão Fm along the Amazon River and across basement rocks further south and in peripheral parts of the shield; 200–250 m a.s.l.
4. **The Atlantic Guiana Surface** (AGS) across basement and sediments of the coastal zone of Suriname north of the Mitaraka Escarpment. The AGS is a vast plain of low, relative relief (<100 m except for residual mountains) with shallow rivers (Figure 2A). It rises from sea level to about 200 m inland around 300 km from the coast.

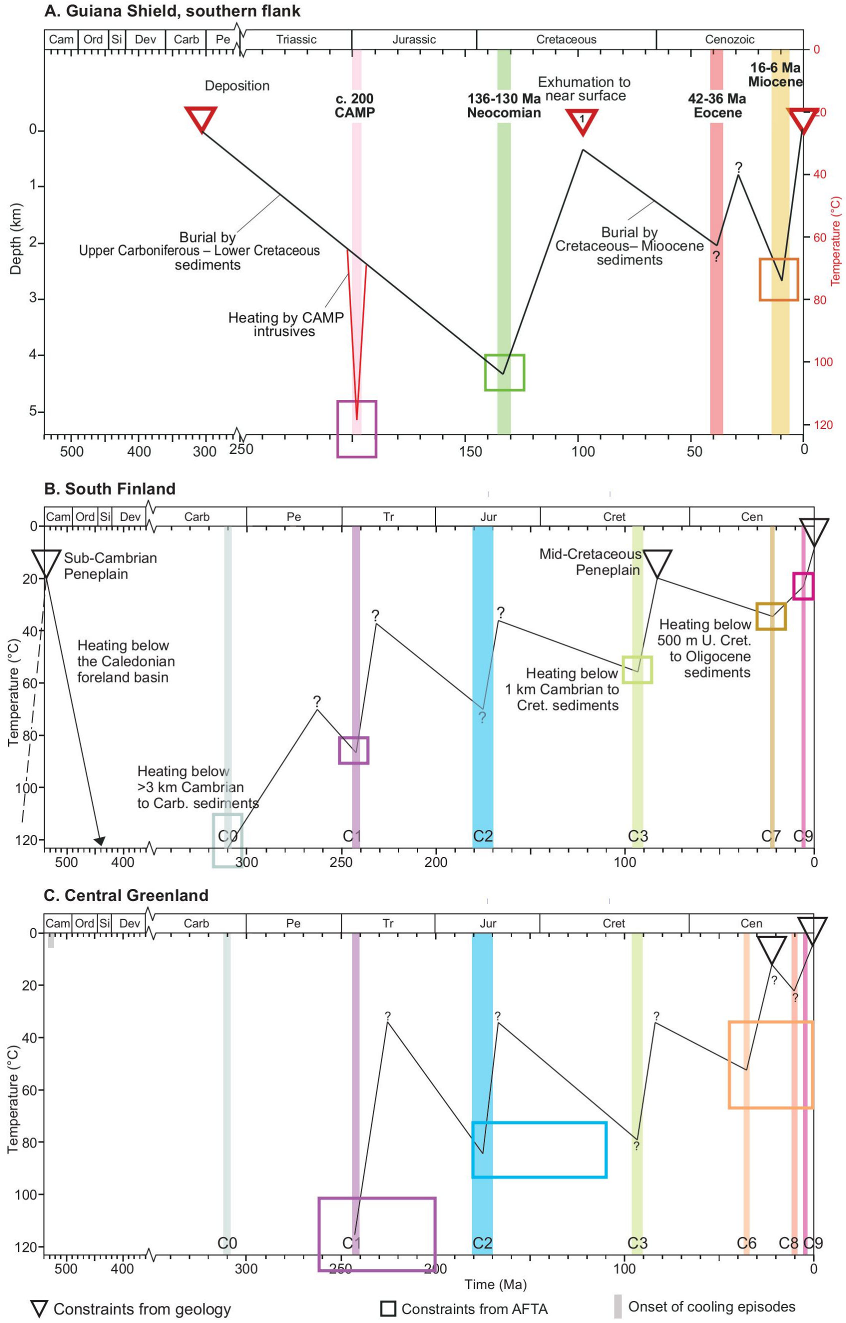

Figure 7. Heating and cooling (burial and exhumation) histories of rocks now exposed at the surface constrained by AFTA data and the stratigraphic record. (**A**) Southern flank of the Guiana Shield [49]: History for upper Carboniferous sediments that crop out near exposed basement. Annotation (1) in triangle: Exhumation to near the surface prior to deposition of Lower Cretaceous sediments (now removed). Red lines: Paleotemperatures from uniform burial-exhumation and heating-cooling histories related to cooling from CAMP intrusives. Constant paleogeothermal gradient of 18 °C/km and surface temperature of 26 °C assumed. (**B**) Coast of southern Finland, OTN boreholes [48, 79]: History of Precambrian rocks exposed on the Sub-Cambrian Peneplain, which is truncated at low elevation by the mid-Cretaceous peneplain at some distance from the coast. Paleotemperature constraints defined by sea-level intercept projections of paleotemperatures defined in the boreholes. (**C**) Central Greenland, GISP2 core [79]: History of Precambrian rocks penetrated below 3 km of ice. Cooling episodes C0–C9 defined in Figure 9. Vertical bands: Onset of cooling episodes from AFTA, width indicate the uncertainty in the estimate. (**A**) Cooling episodes from Figure 5 (Eocene cooling not resolved in samples from this region). (**B,C**) Cooling episodes C0–C9 from Figure 9. (**A,B**) Ranges of paleotemperatures shown as boxes with a height corresponding to the allowed range for the samples in question. The width of the boxes is fixed in centimeters. (**C**) Ranges of paleotemperatures and constraints on the onset of cooling shown as boxes according to the thermal history interpretation. Carb: Carboniferous. Cret: Cretaceous. Jur: Jurassic. U: Upper.

3.1.3. Episodic Burial and Exhumation: Guiana

CAMP intrusives are truncated at the surface across the shield and by the base-Cretaceous unconformity in the Amazon Basin without any known occurrence of extrusive rocks related to this magmatic event [69]. This implies that post-CAMP erosion removed the uppermost parts of the intrusives, and that the bedrock surfaces exposed on the Guiana Shield are erosion surfaces formed in post-CAMP time.

The UGS is the most elevated and therefore the oldest of the planation surfaces. As the surface postdates CAMP magmatism, we identify the denudation that led to its formation with the first post-CAMP episode of exhumation recognized from AFTA; i.e. the Neocomian episode. This also resulted in the formation of the base-Cretaceous unconformity in the Amazon Basin, corresponding to the base-Cretaceous peneplains in the Acre and Solimões basins to the west [80] and in the Andes after the post-orogenic collapse of these mountains [73]. The base-Cretaceous peneplain thus extended across the northern part of the continent.

The LGS cuts across rocks of different age and lithology on the shield and along the Amazon River, where the surface truncates the Paleogene sediments of the Alter do Chão Fm. The timing for the formation of the LGS therefore corresponds to the episode of Eocene exhumation, which removed thick rock columns across the onshore study area and the offshore Casiporé Basin. The LGS correlates with the Eocene 'post-Incaic unconformity' in the Andes formed after renewed post-orogenic collapse [73].

The MGS was therefore the result of exhumation between the Neocomian and Eocene episodes, most likely during the Albian episode which also resulted in the formation of the (now buried) late Albian peneplain on the Demerara Plateau [81].

According to this chronology, the AGS was graded to base level in post-Eocene times, i.e. following the Miocene episode of exhumation, which most likely began in the Tortonian [77, 82, 83]. The Miocene phase raised the LGS along the Amazon River, leading to the incision of the present-day valley and the reversal of the Amazon River. Consequently, (the eastern part of) the Guiana Shield only reached its present elevation after Miocene uplift.

The combination of LTT data with geological and geomorphological observations defines a complex history involving repeated episodes of burial and exhumation, not only of the Guiana Shield and the sedimentary basins north and south of the shield, but of wide areas of northern South America. The Guiana Shield thus acted as an integral part of the region in tandem with the basinal areas such as the Amazon Basin: 'Tectonic reworking' [15, 57] was therefore not confined to the margin of the shield.

3.2. Burial and Exhumation History of the Paleogene Fonseca Formation in the Highlands of the São Francisco Craton

A rare insight into the Cenozoic development of the highlands in the interior of Brazil is possible due to an outlier of the Paleogene Fonseca Formation, located on the edge of the Precambrian São Francisco Craton [84] within the South American supercraton, c. 50 km east of the city of Belo Horizonte (Figure 1). This sediment is preserved in a small, graben-like basement structure c. 800 m a.s.l., and it is unconformably overlain by the undated, ironstone conglomerate of the Chapada de Canga Formation [85]. The age of the Fonseca Fm corresponds to the Eocene–Oligocene boundary [86].

Based on organic geochemistry in a sample from the Fonseca Fm and AFTA from nearby basement, Japsen et al. [87] concluded that this unit reached paleotemperatures between 60 and 80 °C, equivalent to burial under 1.5–2.0 km of cover for a paleogeothermal gradient of 25 °C/km. The timing defined by AFTA spans both the Eocene and Miocene exhumation events identified from regional data, and it remains uncertain whether maximum burial of the Fonseca Fm occurred in late Paleogene or Neogene times. The Fonseca Fm was deposited by a meandering river system [85], so more extensive areas must have been covered by these kilometre-thick deposits of Eocene and younger sediments.

In summary, these observations suggest that the area was low-lying during the deposition of the Fonseca Fm, and that the area subsided during the accumulation of additional fluvial deposits in post-Fonseca times until this overburden was lost during an episode of exhumation that led to the reexposure of the Fonseca Fm. The preservation of the Fonseca Fm within a small graben structure, thus allows us to conclude that this cratonic region experienced significant episodes of positive and negative vertical motion during Cenozoic times.

3.3. Contrary Views

Some studies designed to investigate the balance between onshore denudation and offshore accumulation assume a continual supply of erosional detritus to offshore basins [11, 67]. Such studies, aimed at identifying the response of the cratonic domain to long-term climate change, ignore the episodic nature of cratonic evolution.

The study of Egholm et al. [12] provides another case where the complex history of cratons has been overlooked. These authors used computational simulations to investigate the apparent long-term preservation of significant mountain-range relief in ancient, tectonically inactive orogenic belts. They investigated the Precambrian basement terrain in the western part of the Guiana Shield where elevations reach 2.8 km. Based on the assumption of craton stability, they argued that the mountainous topography with steep slopes had been preserved for several hundred million years. They did not investigate the high topography in the context of regional geology and evidence provided by the landscape itself. Insteadthese authors simply associated old rocks with old topography.

Our study of the burial and exhumation history of north-east Brazil [87] provided results that are comparable with those from the Guiana Shield [49], not least in terms of the synchroneity of episodes of subsidence and uplift between rift basins and margins, as well as the cratonic hinterland. However, these results remain challenged by some authors. For example Peulvast and Bétard [88] argued that the absence of post-Cenomanian sediments in most parts of the north-east Brazil was evidence that they had never been present, despite LTT data showing that a kilometre-thick sequence had accumulated and had subsequently been removed across this region [87, 89]. Jelinek et al. [90] interpreted LTT data from north-east Brazil in terms of continuous cooling, disregarding the presence of Phanerozoic sediments and well-known planation surfaces. Based on these omissions, the authors argued that they favoured a 'parsimonious approach' in which the simplest model that is consistent with both LTT data and independent geological evidence is considered optimal.

However, simple models are not necessarily the most appropriate. The considerations presented here emphasise the need to combine thermochronological data with evidence from stratigraphy and landscape in surrounding regions [22]. Failure to do so results in a false impression of the tectonic development.

4. The Baltica Supercraton

4.1. The Baltic Shield

Precambrian crystalline basement dominates the Baltic Shield, which extends across Sweden and Finland, forming part of the Baltica supercraton. However, at restricted locations, remnants of Paleozoic and Mesozoic sediments rest on the basement (Figure 8), documenting a complex Phanerozoic history of vertical movements of the crust.

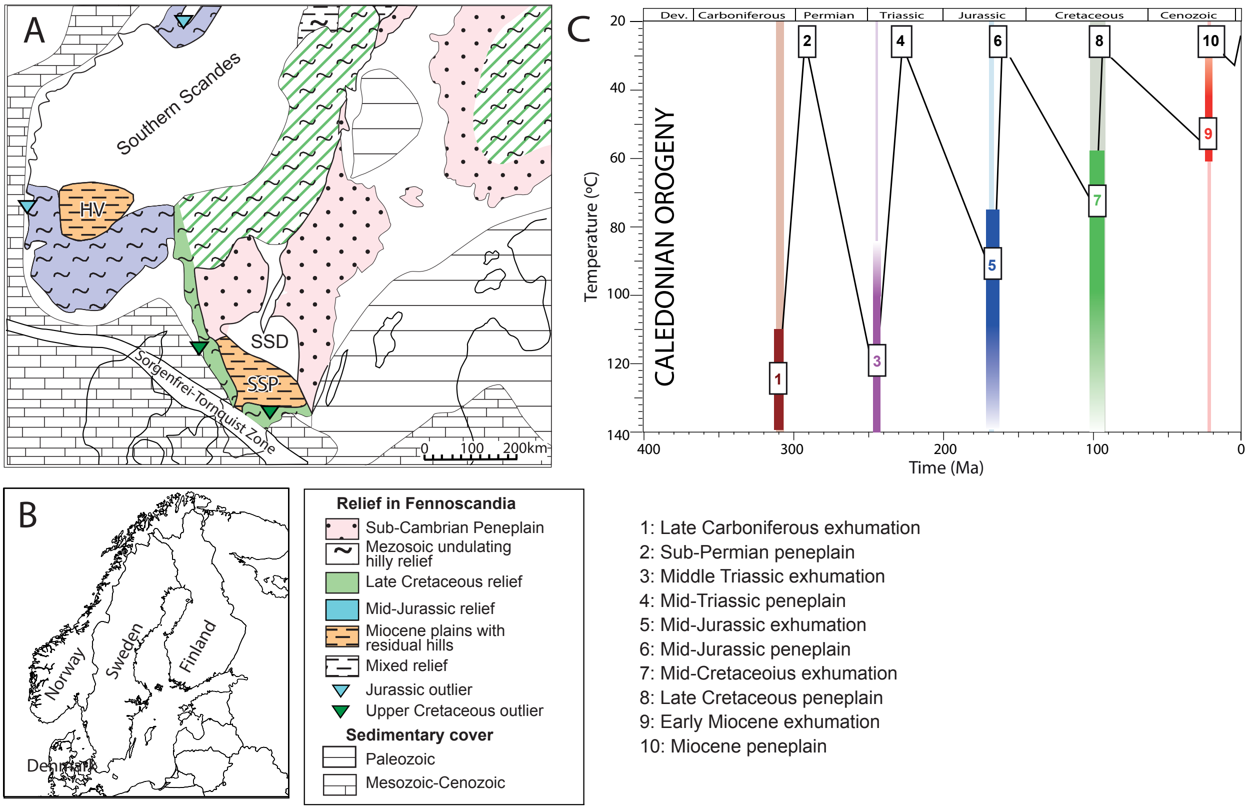

Figure 8. Peneplains and thermal history across Fennoscandia. (**A**) Basement relief in relation to the cover rocks in southern Fennoscandia (modified after [48]). Green diagonal shading indicates an inferred Cretaceous age. Bonow et al. [37] provide more details regarding the relief of the Southern Scandes. HV: Hardangervidda. SSD: South Sweden Dome. SSP: South Smøaland Peneplain. (**B**) National boundaries. (**C**) Sketch illustrating the thermal history of rocks at or close to the present-day surface across Fennoscandia (modified after [48, 79]). The combination of thermal history constraints and the presence of peneplains defines a history of episodic exhumation and re-burial. While no single location exhibited a thermal history precisely as shown, most regions underwent the majority of the episodes shown to some degree. The correlation between cooling episodes and the resulting peneplains shows that exhumation to the surface must have been quite rapid.

Lidmar-Bergström and co-authors used the relations between cover rocks and distinct peneplains across the Precambrian basement to draw attention to Scandinavia (and Finland) as an example of Phanerozoic uplift and subsidence. Based on such observations, they defined the formation of the South Swedish Dome (up to 400 m a.s.l.; Figure 8) through multiple Phanerozoic episodes of burial and subsequent exhumation [26, 91–94].

This style of history, in which the supposedly stable shield has been reshaped through Phanerozoic episodes of uplift and exhumation followed by subsidence and burial, is very different from the monotonic emergence and cooling history often envisaged for the Baltic Shield [4, 8, 95]. But episodic development is supported by evidence from our thermochronological studies [48, 54, 79, 96] which show that rocks now exposed at the surface, were heated to temperatures of 100 °C or more prior to late Paleozoic cooling, requiring the former presence of a kilometre-thick early Paleozoic cover above the Sub-Cambrian Peneplain a conclusion also reach by earlier studies [97–101]. Linking thermochronological results with landscape evidence shows that late Paleozoic cooling and exhumation was followed by further episodes of burial and exhumation through Mesozoic and Cenozoic times, as described below.

4.1.1. Episodes of Exhumation: Baltica

Green et al. [48] reported AFTA data and associated thermal history constraints in samples of Precambrian and Caledonian basement and Phanerozoic sediments and igneous rocks from across Fennoscandia; i.e. Norway and the Baltic Shield exposed in Sweden and Finland. Japsen et al. [79] provided a synthesis of the AFTA data from Greenland, Fennoscandia and adjacent areas (Figures 9 and 10), defining a series of roughly synchronous episodes of exhumation in these areas. The broad synchronism between the onset of cooling across this wide region emphasises the uniformity of these events. Specifically, six key episodes affected the Baltic Shield in Sweden and Finland (as well as the Scandinavian margin in Norway) since the Devonian collapse of the Caledonian mountains in East Greenland and Scandinavia [102], viz: Beginning in the late Carboniferous, Middle Triassic, mid-Jurassic, mid-Cretaceous, early Miocene and early Pliocene (Figures 9 and 10) [48, 79]. Interestingly, whereas early Miocene exhumation affected Fennoscandia, late Miocene exhumation affected Greenland, suggesting that these episodes had their origin on the respective continental plates.

4.1.2. Peneplains: Baltica

Several erosion surfaces (peneplains) with well-constrained ages have been recognized across Fennoscandia (Figure 8), providing direct evidence of when underlying rocks were exposed at the surface [26, 29, 54, 96]. Here we focus on the peneplains that are defined across the Baltic Shield in Sweden and Finland and their relation to the episodes of exhumation that led to their formation (Figure 9).

Exhumation that most likely began around 600 Ma [48] resulted in the formation of **the Sub-Cambrian Peneplain** (Section 2.2). The surface extends across large parts of Sweden (protected by a lower Paleozoic cover in south-western Sweden) and within a wide zone along the coasts of Finland [26]. Within the Gulf of Bothnia, up to 3 km of Paleozoic sediments rest on the Sub-Cambrian Peneplain and the underlying bedrock of the Baltic Shield [103, 104].

Exhumation that began in the late Carboniferous led to the formation of **a sub-Permian unconformity** in the North Sea [105, 106]. In Scandinavia this tectonic episode is represented by unconformities; e.g. in the late Carboniferous—Early Triassic Oslo Rift (Figure 10A); Olaussen et al., 1994; Larsen et al., 2008), in the Baltic Sea and in the Sorgenfrei-Tornquist Zone [107, 108].

Exhumation that began in the Middle Triassic resulted in the formation of **a mid-Triassic peneplain**, documented in the Kattegat, off south-west Sweden [109]. In southernmost Sweden it corresponds to the sub-Mesozoic denudation surface that truncates all traces of the superficial effusives which must have resulted from a late Paleozoic magmatic event [96, 110]. In the offshore continuation of the Oslo Rift, a major unconformity separates upper Paleozoic from Mesozoic sequences [111].

Exhumation that began in the mid-Cretaceous resulted in the formation of a deeply weathered **mid-Cretaceous peneplain** (the sub-Cretaceous hilly relief of Lidmar-Bergström et al. [26]) over large parts of Sweden and in central Finland. In southernmost Sweden, Campanian sediments and widespread occurrences of flint erratics derived from a former cover of Upper Cretaceous chalk occur on this surface with kaolinized basement rocks [25].

Exhumation that began in the early Miocene resulted in the formation of **a Miocene peneplain** graded to sea level, today represented by the sub-horizontal plateau surfaces (Figure 8A); Hardangervidda (1.2 km a.s.l.; Southern Scandes) and the South Smøaland Peneplain (0.2 km a.s.l.; the South Swedish Dome) as well as the base-Miocene unconformity offshore north-west Europe. Uplift that began in the early Pliocene raised these surfaces to their present elevation.

Furthermore, **a mid-Jurassic peneplain** with hilly relief defines the slopes of the Southern Scandes in Norway [37, 79]. The mid-Cretaceous tectonic episode resulted in folding of this peneplain, which was subsequently truncated by sub-horizontal mid-Cretaceous, Paleocene and Miocene peneplains, resulting in the characteristic shape of the Southern Scandes with elevated plains above the dipping flanks of the mountains (Figure 3B).

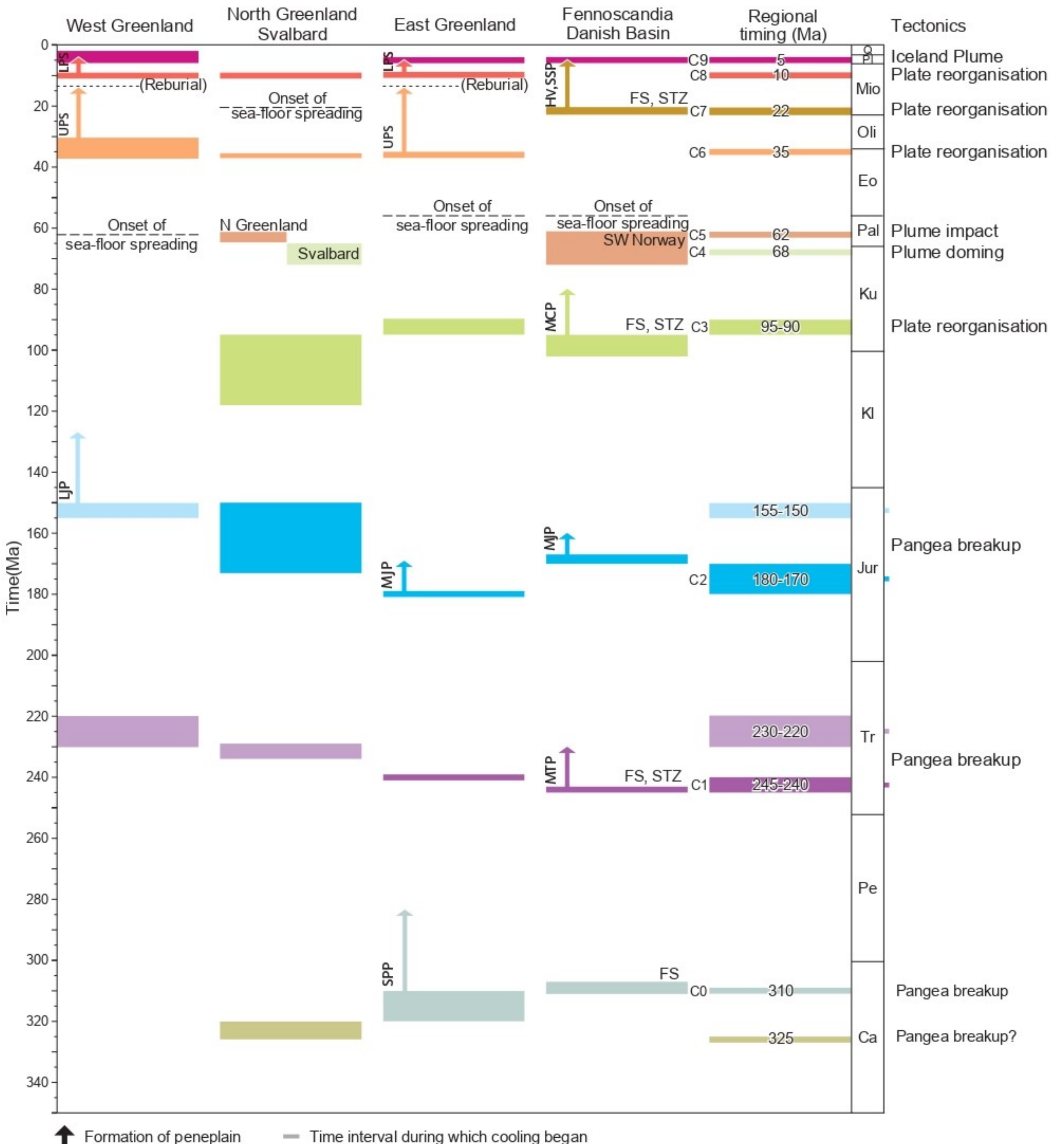

Figure 9. Onset of post-Caledonian episodes of regional exhumation (cooling) based on AFTA: data and time intervals for peneplain formation [79]. Vertical extent of the horizontal, coloured bands in the four left-hand columns indicate uncertainty for the onset of the exhumation episodes. Duration of peneplain formation (coloured arrows). The right-hand, coloured column indicates the regional timing for the onset of exhumation in each episode based on data for the areas in the four columns. Intervening subsidence and burial not shown. Correlation with tectonic events indicated in the right-hand column. Iceland Plume: Uplift along continental margins due to dynamic support by the Iceland Plume. Pangea break-up: Epeirogenic uplifts during break-up of Pangea. Plate reorganization: Uplift starting at the same time as plate reorganization. Plume dome: Doming above the Iceland Plume rising through the upper mantle. Plume impact: Onset of sea-floor spreading west of Greenland and inversion of fault zones during the onset of the Eurekan Orogeny. Timing of Maastrichtian domal uplift on Svalbard and of Paleocene inversion of fault zones in North Greenland from AFTA data adjusted by stratigraphic constraints from Canadian High Arctic [112]. Timing of continental break-up from Oakey and Chalmers [113], Gaina et al. [114], Dumais et al. [115]. FS: Fennoscandia. HV: Hardangervidda. LJP/MJP: Late/Mid-Jurassic Peneplain. LPS/UPS: Lower/ Upper Planation Surface. MCP: Mid-Cretaceous Peneplain. MTP: Mid-Triassic Peneplain. SPP: Sub-Permian Peneplain. SSP: South Smøaland Peneplain. STZ: Sorgenfrei-Tornquist Zone.

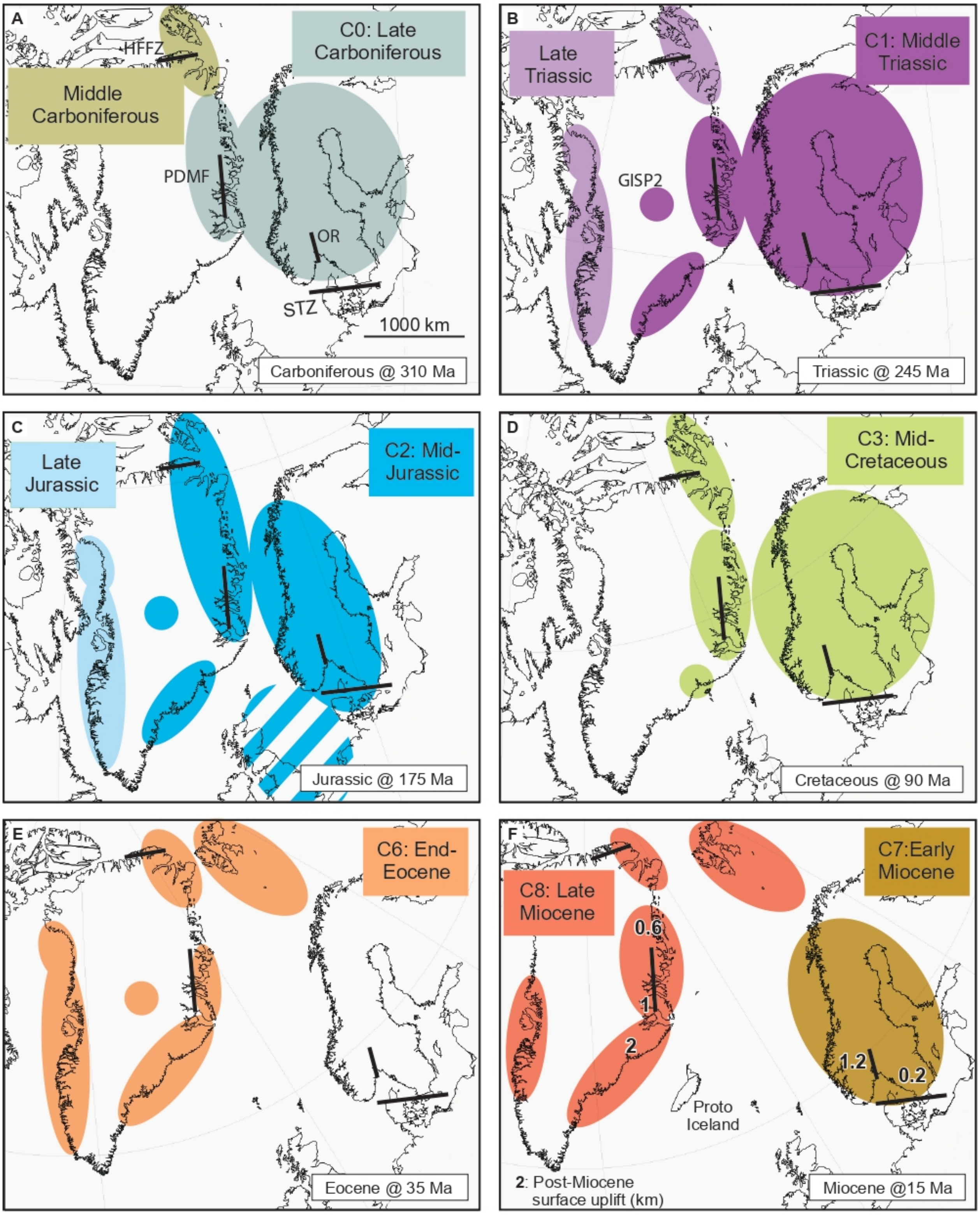

Figure 10. Regions of broadly synchronous episodes of exhumation defined from AFTA from Greenland, Fennoscandia and adjacent regions [79]. The maps illustrates that both Precambrian and Caledonian basement and adjacent basins were affected alike during these episodes of exhumation. Location of present-day coastlines and plate configurations for the designated times [116]. (**B**) Location of the GISP2 rock sample indicated in central Greenland. (**C**) Outline of the mid-Jurassic 'Central North Sea Dome' indicated with hatched colour [117]. (**F**) Post-Miocene surface uplift estimated from elevation of Miocene peneplains [47, 54, 96]. Black lines: faults. HFFZ: Harder Fjord Fault Zone. OR: Oslo Rift. PDMF: Post-Devonian Main Fault system. STZ: Sorgenfrei-Tornquist Zone.

In summary, the presence of these well-dated peneplains across this portion of Baltica is direct evidence of the vertical movements of the craton throughout the Phanerozoic. The preservation of the surfaces to the present day, is evidence that the surfaces were buried and re-exposed, as pointed out by Lidmar-Bergström et al. [26]. In this way, the landscape provides direct evidence of episodic burial and exhumation.

4.1.3. Episodic Burial and Exhumation: Baltica

As discussed above peneplains of different age occur in basement rocks over wide areas in Fennoscandia (Figure 8A). However, each of these peneplains had a much more regional extent at the time of their formation. For example, the Sub-Cambrian Peneplain, which is present onshore and offshore southern Sweden, must have been present in the intervening zone along the coast of southern and western Sweden. Here the removal of the Paleozoic cover during mid-Cretaceous exhumation led to re-exposure of the basement and thus to destruction of the Sub-Cambrian Peneplain and formation of the hilly mid-Cretaceous peneplain (Figure 8A). Another example is the Miocene peneplain preserved in bedrock on the Hardangervidda plateau in southern Norway. The surface originally also extended across a Jurassic–Oligocene sedimentary succession above the Jurassic hilly relief on the flanks of the Southern Scandes. A similar configuration occurs in southern Sweden, where the Miocene South Småland Peneplain truncates the mid-Cretaceous peneplain. Figure 3B illustrates both situations.

Furthermore, evidence for the exhumation episodes revealed by AFTA, resulting in creation of these peneplains, is detected over much of Fennoscandia and adjacent areas (Figure 10). Formation of peneplains define periods of bedrock exposure, so combining evidence for the presence of peneplains with results from AFTA showing cooling from distinct paleothermal maxima shows that episodes of exhumation must have been followed by reburial to attain the paleotemperatures defined from AFTA (Figure 8C).

In summary, combining thermal history constraints with the presence of peneplains defines a history of episodic exhumation and reburial, even in the basement terrains of Fennoscandia where post-Caledonian cover rocks are largely absent.

4.2. The Importance of LTT Data from Deep Boreholes

LTT data from deep boreholes allows for confident estimation of (1) paleogeothermal gradients by evaluating the variation of paleotemperatures for a specific episode with depth and (2) for definition of the younger cooling episodes at depth, where fission tracks formed during the earlier history are no longer preserved. AFTA data from the OTN boreholes drilled near Helsinki, Finland, and the Gravberg-1 borehole in central Sweden (both to c. 6 km depth) therefore provide important information about the Phanerozoic burial and exhumation of the Baltic Shield [48].

Overall, the results from each borehole can be described by five linear temperature-depth profiles with gradients similar to the present-day value, suggesting that paleotemperatures in each episode predominantly represent deeper burial, with cooling due mainly to exhumation. Thus, significant thicknesses of rock were present over the cratonic bedrock in Finland and Sweden prior to these cooling episodes and were subsequently removed, leaving little trace in the geological record. By combining the estimated paleotemperatures with the presence of specific peneplains defining when the bedrock was exposed at the surface, it is possible to define the thicknesses of sediments that subsequently accumulated on these surfaces (Figure 7B).

The dominant post-Caledonian paleothermal episodes defined from AFTA in these boreholes in the Baltic Shield are generally synchronous with those from locations closer to the margin of NW Europe in Norway, the only significant difference being the smaller magnitude of cooling in each episode in the cratonic core compared to the margin. These results can be explained simply by a thinner sedimentary cover in Finland compared to regions to the west, possibly combined with a lower thermal gradient.

4.3. Contrary Views

Kukkonen et al. [8] presented a re-evaluation of the AFTA data in samples from Finland from Green et al. [48], resulting in a different style of exhumation history involving burial of the Sub-Cambrian Peneplain followed by '*gradual, continuous unroofing . . . since the early Permian*'. Thus, these authors accepted the geological evidence of the sub-Cambrian Peneplain while dismissing evidence for other episodes of surface exposure referenced by Green et al. [48]. Kukkonen et al. [8] reported that they found the episodic thermal history framework adopted by Green et al. [48] to be not '*geologically feasible, at least not in the Fennoscandia case*'. On the basis that inverse modelling of LTT data is ambiguous (with which we agree—see Section 2.1), their approach was to '*prefer to keep it as simple as the geological data suggests*'. One problem with this approach is that geological histories tend to be complex, and thermal histories not to be simple [118]. In addition, the question arises as to what geological evidence is considered. Kukkonen et al. [8] chose to reference only the Sub-Cambrian Peneplain, whereas Green et al. [48] took into account evidence across a wider region for times at which the crust was being uplifted and eroded to the surface in some places, leaving evidence in terms of peneplains and unconformities across a wide area, resulting in a generalised history as shown in Figure 8C. If cratons act as coherent bodies, as generally assumed, then it seems straightforward to extend local evidence for uplift across the shield.

As discussed in Section 2.1, LTT data cannot define periods of lower temperature, and therefore without imposing external constraints, a post-early Permian history involving '*gradual, continual unroofing*' is the inevitable result, as reported by Kukkonen et al. [8]. We suggest that geological evidence across a wider region must be considered (consistent with the concept that cratons behave as rigid bodies), and therefore that a history involving multiple episodes of burial and exhumation is more realistic.

5. The Laurentia Supercraton

5.1. East and Central Greenland

Greenland is part of the Laurentia supercraton and is itself composed of a patchwork of cratonic components [119]. We focus on East Greenland which was juxtaposed to Fennoscandia prior to break-up of the North-East Atlantic at the Paleocene–Eocene transition [114] and on central Greenland where little is known about the geology [120]. However, the GISP2 drillcore penetrated c. 3 km of ice and 1.6 m into the bedrock (Figure 10B). The bedrock material consisted of 48 cm of till, including boulders and cobbles, overlying grey biotite granite of Archean age, comprising the true bedrock [121, 122].

The basement terrain along the east coast of Greenland north of 70°N, was involved in the Caledonian Orogeny that culminated in the collision of Laurentia and Baltica in the Silurian [102]. The Caledonian Orogen collapsed in the Devonian, and the bevelled Caledonian basement (the sub-Permian peneplain) was transgressed by the sea in the late Permian [123, 124].

Important phases of rifting took place along the East Greenland margin during the Carboniferous–Cretaceous (along the so-called Post-Devonian Main Fault; Figures 10A and 11(A1)) prior to the final break-up [124–128]. Sediments of these rift basins are exposed onshore, mainly north of 70°N, and they contain several significant unconformities marking key tectonic episodes ([129] and references therein), viz. latest Carboniferous—early Permian, Early—Middle Triassic, Early—Middle Jurassic, earliest Cretaceous and Turonian.

Paleogene volcanics occur along the coast between 68 and 75°N and dominate the bedrock along Blosseville Kyst south of Scoresby Sund, 68–70°N [130], Figure 11(B1). Here the voluminous flood basalts erupted onto a largely horizontal lava plain near sea level at the Paleocene–Eocene transition [128, 131]. Yet today, the highest mountain in Greenland and in the North-East Atlantic domain is in this region (Gunbjørn Fjeld, 3.7 km a.s.l., 69°N). The underlying Precambrian basement was therefore involved in km-scale vertical motion since the Eocene.

Despite this geological evidence for subsidence and uplift of the East Greenland margin, many studies have assumed monotonic cooling and exhumation thought to be typical of cratonic regions, leading to the conclusion that the mountains in North-East Greenland are remnants from the Caledonian Orogeny [9, 132].

Here we summarize arguments based on SLA, geological evidence and LTT leading to the conclusion that Greenland has undergone a number of episodes of burial and exhumation since the Caledonian Orogeny.

5.1.1. Episodes of Exhumation: Greenland

Japsen et al. [79] provided a review of published AFTA data from Greenland. The coverage is limited by the extent of the thick Greenland ice sheet, but many samples in East Greenland were collected at considerable distance west of the PDMF boundary fault and one basement sample was obtained from the GISP2 drillcore in central Greenland. The data define a number of episodes of exhumation following the Devonian collapse of the Caledonian mountains [102, 133]. In addition to some episodes of local importance, eight key episodes appear to have affected most of the region, beginning in the late Carboniferous, Middle Triassic, mid-Jurassic, earliest Cretaceous, mid-Cretaceous, late Eocene, late Miocene and early Pliocene (Figures 9 and 10).

The episodes that affected East Greenland prior to break-up are broadly synchronous with exhumation episodes in Fennoscandia, as well as North and West Greenland and further afield in Svalbard (Figure 9). AFTA data from Fennoscandia do not resolve cooling related to the end-Eocene episode, but an end-Eocene unconformity offshore North-West Europe reflects a dramatic change in the basin configuration [134]. Early Miocene exhumation affected Fennoscandia and the offshore sedimentary basins of North-West Europe, but there is no evidence of regional exhumation at that time in Greenland. In contrast, late Miocene exhumation affected Greenland, Svalbard and the Barents Sea, but not Fennoscandia. Early Pliocene uplift and incision, which affected both Greenland, Fennoscandia and surrounding regions, is resolved in AFTA data and deduced from the elevation of Miocene peneplains in Greenland and Fennoscandia.

These observations suggest that Greenland and Fennoscandia were affected by common events at key moments in the geological evolution, which implies common controlling mechanisms. In contrast, the asymmetric history of Miocene uplifts across the North-East Atlantic indicates control by different processes for the conjugate plates after break-up (Section 8).

5.1.2. Peneplains: Greenland

Two elevated erosion surfaces dominate the partly glaciated landscape of East Greenland (68–78°N), Figures 11(A2,B2) [46, 47]. **The Upper Planation Surface** (UPS) is typically at elevations around 2 km, but south of 70°N elevations reach 3 km. The surface cuts across basement and Paleogene basalts, indicating that it was graded to the base level of the Atlantic Ocean in post-basalt times and subsequently uplifted (Figure 12). The UPS formed prior to the deposition of mid-Miocene lavas that rest on it [46, 135]. The surface is thus not formed by glacial processes.

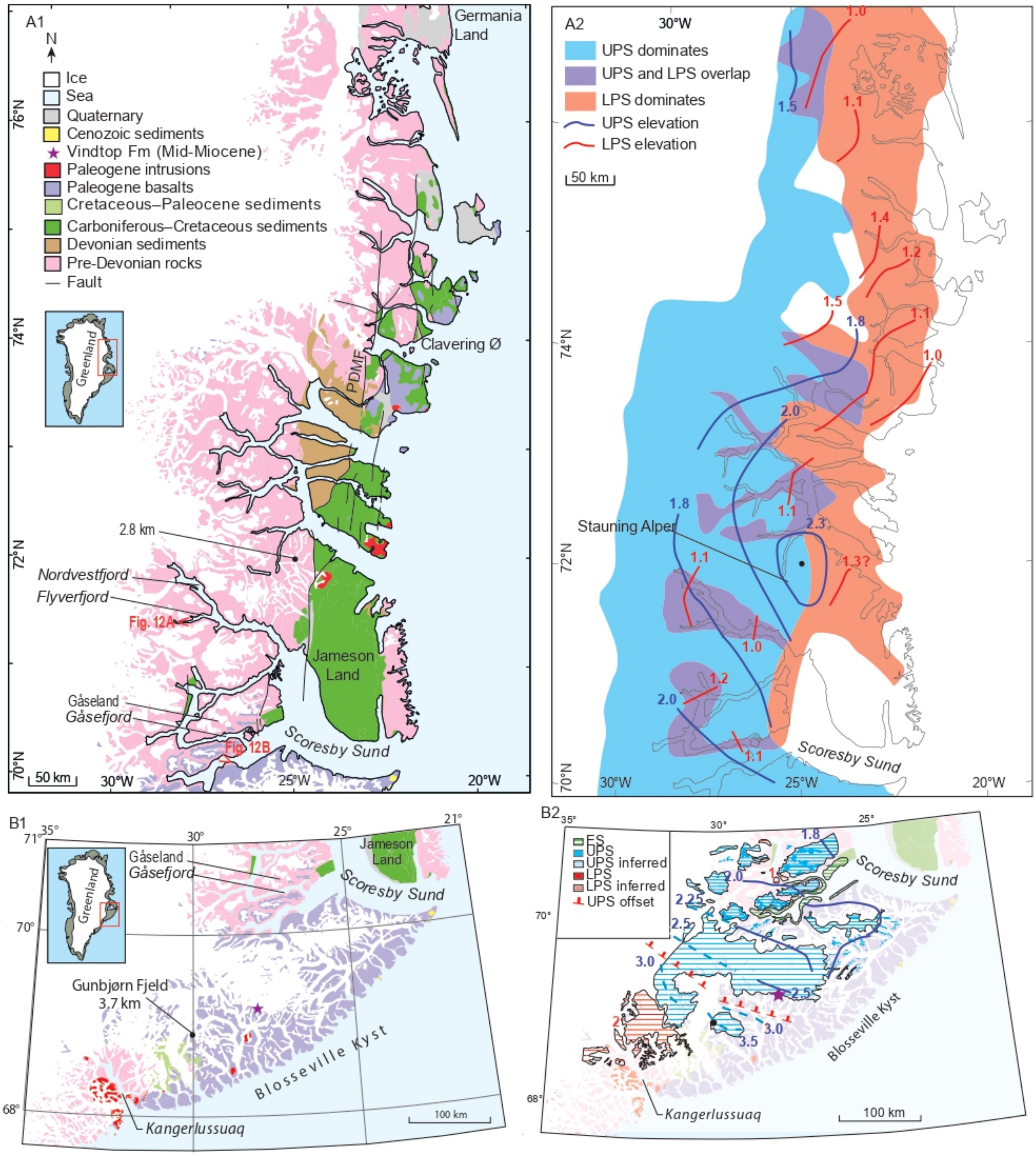

Figure 11. Geology and peneplains in East Greenland. (**A1,A2**) North-East Greenland (70–78°N). (**B1,B2**) Central East Greenland (68–70°N). (**A1,B1**) Geology. North of 70°N crystalline basement (Precambrian and Caledonian) and Devonian rocks dominate west of the Post-Devonian Main Fault (PDMF) with Carboniferous–Cretaceous rift basins to the east. Between 68 and 70°N, Paleogene flood basalts dominate, but patches of basalt occur as far north as 75°N. Several Paleogene intrusive centres occur along the coast. Location of photos in Figure 12. (**A2,B2**) Peneplains. Extent and elevation of the Upper and Lower Planation Surface (UPS and LPS) and the sub-basalt etch surface (ES). The UPS is typically 2 km a.s.l., identified mainly south of 74°N at some distance from the coast. North of 74°N, the UPS is identified only as small remnants close to the Greenland ice sheet, but south of 70°N elevations reach 3 km (**B2**). The LPS is typically 1 km a.s.l. and coalesces to form a coherent surface towards the coast. Note the dome structure of the UPS centred on Stauning Alper, which suggests tectonic doming after formation of the UPS. The LPS extends over wide areas at the head of Kangerlussuaq, where it reaches an elevation of c. 2 km (**A2**), but it occurs only as valley benches on southern Milne Land and in the areas west of Milne Land. Geology in background (**B2**). Bonow et al. [46], Illustrations modified after Bonow and Japsen [47].

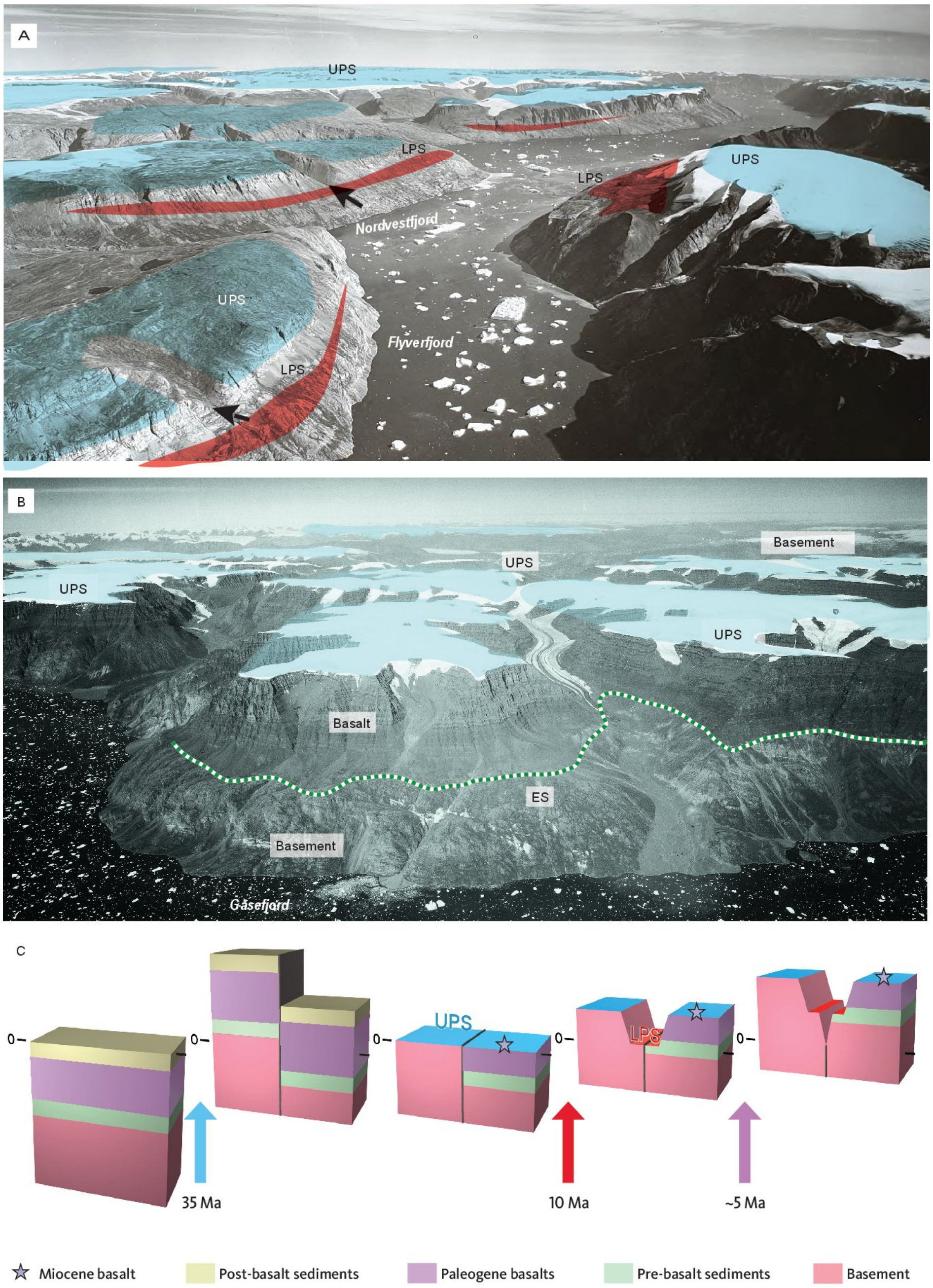

Figure 12. Peneplains in East Greenland. (**A**) View north-east across Flyverfjord and Nordvestfjord in the interior basement terrain partly covered by snow and thin ice caps (modified after [47, 79]). Valley benches formed by incision of the Lower Planation Surface (LPS, red, c. 1000 a.s.l.) below the Upper Planation Surface (UPS, blue, c. 1800 m a.s.l.); photo location in Figure 11(A1). The LPS was graded to sea level during late Miocene incision that began at 10 Ma. The UPS was graded to sea level after uplift that began at 35 Ma. These surfaces reached their present elevation af uplift that began at 5 Ma. Note the V-shaped valleys (black arrows) that demonstrate that rivers, not glaciers, dominated the landscape during the formation of the LPS in the late Miocene. (**B**) View north-west across Gåsefjord and Gåseland (modified after [46, 47]). The UPS (c. 1800 m a.s.l.) cuts across Eocene basalts and basement (in the background); photo location in Figure 11(A1). About 700 m of the basalts have been removed from above Gåseland [127]. The etch surface in basement (ES) defines the base of the basalts (green, dashed line). (**C**) Block diagrams illustrating the development of the East Greenland margin since maximum burial below a Paleogene succession of volcanics and sediments by end of the Eocene [129]. Three events of uplift and erosion (end-Eocene, late Miocene and early Pliocene) led to the formation of the present-day landscape with two elevated peneplains, UPS and LPS. This configuration was established in pre-glacial times, i.e. prior to the extensive glaciations of the Northern Hemisphere towards the end of the Pliocene [136]: (1) Mid-Miocene basalt flows, c. 69°N [135] rest on the UPS, and (2) a fluvial valley system is associated with the LPS (black arrows in **A**).

The Lower Planation Surface (LPS) forms fluvial valley benches at c. 1 km a.s.l., incised below the UPS in the interior basement terrains, but the LPS reaches elevations of up to 2 km south of 70°N. The LPS is thus younger than the UPS, which implies that it formed post mid-Miocene. Towards the coast, the valley benches of the LPS merge to form a coherent surface that defines flat-topped mountains. This shows that the LPS was graded to near sea level and was subsequently uplifted.

The uplift of the LPS led to re-exposure of **a Mesozoic etch surface** below the Paleogene basalts (Figure 12B). The presence of marine, Middle Jurassic sandstones on this weathered surface shows that it is the result of Jurassic exhumation. Likewise, a remnant of a sub-Permian peneplain was exhumed [137].

Episodes of Neogene tectonic uplift thus shaped the stepped landscape and elevated topography in North-East Greenland.

5.1.3. Episodic Burial and Exhumation: Greenland

The combination of LTT data with SLA and observations from the stratigraphic record, defines eight regional episodes of exhumation in the post-Caledonian development of East Greenland, even affecting central Greenland [79, 129]:

1. Late Carboniferous exhumation extended across the basement terrains west of the sedimentary basins and into the rifted margin. The exhumation resulted in the formation of a sub-Permian peneplain mapped in North-East Greenland [124, 137].

2. Middle Triassic exhumation led to removal of a thick rock column in the hinterland of the rift basins (even in central Greenland based on AFTA data from the GISP2 sample; Figure 7C), producing thick siliciclastic deposits within the rift system.

3. Mid-Jurassic denudation affected most of the study area, even far into the hinterland (including central Greenland based on AFTA data from the GISP2 sample) and produced a weathered basement surface with a hilly relief. Major basins subsided and received sedimentary input from their eroding margins.

4. Earliest Cretaceous uplift and erosion along the rifted margin—but also at a considerable distance from the rift—accompanied the Mesozoic rift climax and produced coarse-grained sedimentary infill of the rift basins.

5. Mid-Cretaceous exhumation initiated the removal of Cretaceous post-rift sediments, that had accumulated above the Mesozoic rifts and their hinterland.

6. End-Eocene uplift initiated the removal of a thick post-rift succession that had accumulated after break-up and produced a peneplain near sea level, the UPS, which extends far west of the rift system in North-East Greenland. The surface even extends into the central part of northern Greenland, below the Greenland ice sheet [79, 138], a conclusion supported by AFTA data from the GISP2 sample.

7. Late Miocene exhumation affected the entire region, even far into the interior highlands. This incision resulted in the formation of the LPS.

8. Early Pliocene uplift initiated the rise of the UPS and the LPS to their present elevations and the formation of the present-day landscape through fluvial and glacial erosion. Analysis of subglacial valley networks [138, 139] define two phases of incision, corresponding to the late Miocene and early Pliocene episodes of exhumation (Figure 12).

Furthermore, late Maastrichtian uplift and erosion affected the North American Arctic, the Lomonosov Ridge, Svalbard and the Barents Sea, parts of Greenland, both onshore and offshore ([79, 140] and references therein). Evidence for this episode is not resolved in AFTA data from Greenland, but it is documented by LTT data elsewhere in the region.

5.1.4. Discussion

These observations show that the episodes of burial and exhumation affected areas far into the cratonic regions of East Greenland; e.g. 150 and 500 km west of the rift basins resolved in outcrop samples and in the central Greenland GISP2 sample (Figure 7C), respectively. The cratonic hinterland is therefore not characterized by the often-assumed stability, but by a repeated history of vertical movements.

Most of the Paleozoic–Mesozoic episodes of exhumation have also been resolved in central West Greenland, although in some cases delayed relative to the east coast, likely reflecting a later onset of the rifting phases [79, 141–143]. However, the episodes of Cenozoic exhumation appear to have occurred simultaneously on both coasts. This coincidence corresponds to the presence of the elevated peneplains, UPS and LPS, also on the west coast [24, 47].

The late Neogene uplifts in East Greenland resulted in formation of the highest mountains of the North-East Atlantic domain. The two highest summits are in Precambrian terrain, Gunbjørn Fjeld with the top parts in Paleogene basalts and Mount Forel (3.4 km a.s.l., 67°N), while the third highest summit is in Caledonian basement, part of Stauning Alps (2.8 km a.s.l., 72°N). The age of the bedrock thus provides no clue to when these summits reached their present-day elevations.

The end-result of these tectonic episodes is the present-day bedrock configuration of Greenland with a low-relief, sub-glacial surface in the interior of Greenland near sea level, surrounded by coastal mountains. The landscape is primarily developed in basement rocks of either Precambrian or Caledonian age, parts of the supposedly stable Laurentian supercraton.

5.2. Contrary Views

Despite the geological evidence for episodic subsidence and uplift of the East Greenland margin, many studies have assumed monotonic cooling and exhumation.

Pedersen et al. [9] for example, analysed LTT data from basement samples across northeastern Greenland and concluded that the region underwent continuous exhumation over the last 300 million years, and thus that the mountains there represent the eroded remnants of the original Caledonian topography, echoing the ideas of Nielsen et al. [144]. However, their study area contains outcrops of Upper Carboniferous and Middle Jurassic sediments, defining times at which the underlying basement was at the surface, in conflict with an interpretation of slow continuous denudation [145].

Johnson and Gallagher [146] interpreted LTT results from samples of Carboniferous sandstones from a vertical transect on Clavering Ø as defining progressive cooling through late Paleozoic and Mesozoic times prior to accelerated Cenozoic cooling. Palaeogene basalts rest on the section sampled, showing that their uppermost sample must have been at near-surface temperature in the Paleogene. However, their analysis took no note of this basic constraint on the thermal history of the succession, leading to serious underestimation of final Mesozoic cooling and Palaeogene re-burial prior to the onset of Cenozoic cooling [147].

5.3. North American Craton

Here we review evidence of episodic vertical movements of the North American Craton, which contain regions of exposed basement as well as cratonic basins more than 4 km deep [17]. The results of these studies support our general thesis that such behaviour is a general property of cratonic regions.

Flowers and Kelley [148] presented AHe data in samples from cratonic basement at depths around 300 metres in a borehole located in the US midcontinent region (Kansas). Importantly, the basement is overlain by thin sequences of Cretaceous, Permian and Cambrian sedimentary units, and each of these units provides constraint on times when the underlying basement was at or close to the surface. Application of these constraints in the thermal model revealed that during each of the unconformities within the section, the underlying basement was heated due to burial by km-scale thicknesses of rock and then exhumed to the surface, with the maximum temperature reached prior to the onset of cooling declining through time.

McDannell et al. [149] presented AFT data from cratonic basement samples in northern Canada. These samples were close to outcrops of Paleozoic carbonates, while Cretaceous sediments occur over the wider region. The thermal history interpretation derived by McDannell et al. [149] showed that the basement underwent two major episodes of burial and exhumation, with cooling in each corresponding to unconformities within the sedimentary section of the Hudson Bay Basin. They demonstrated that the Hudson Bay sedimentary succession is the remnant of a more extensive and thicker sedimentary cover than is preserved. Thus, this study provided evidence of episodic burial and exhumation of cratonic basement, similar to that described in the studies reviewed above.

As mentioned in the Introduction, Sloss [19, 150] reported evidence for kilometre-scale episodic burial and exhumation of the North American craton based on analysis of stratigraphic trends within the overlying sedimentary successions. This crucial evidence, apparently given little credence in many circles based on the lack of reference in later works, shows that the evidence we have discussed here does not represent any artefact of LTT methods, and remains a characteristic of craton behaviour.

6. Other Regions

Green et al. [22, 29] reviewed evidence from a number of basement regions which reveal histories involving episodic kilometre-scale burial and exhumation. Some of these regions are cratonic in the strict sense, while others are located more peripherally to cratonic cores, some fall within the regions defined as ‘supercratons’ by Pearson et al. [14] and some are not cratonic but show similar behaviour. All display a similar pattern of vertical movements through time, involving deposition of major thicknesses of sedimentary cover subsequently removed by exhumation in a number of episodes. This evidence is briefly reviewed below.

6.1. The Australia Supercraton

Weber et al. [151] reported that the combination of AFT data from the Yilgarn craton of Western Australia and the presence of sporadic outcrops of Permian sediments showed that basement rocks at or close to the surface today underwent late Carboniferous—early Permian exhumation before being re-buried to depths of 1–2 km prior to a second phase of Late Paleozoic—Mesozoic exhumation. Further details of the exhumation of the region are provided by Kohn and Gleadow [20].

Holford et al. [152] reported AFTA data from basement rocks forming a late Carboniferous glacial pavement and from overlying Permian sandstones on the Fleurieu Peninsula, South Australia. Integrating the AFTA data with stratigraphic constraints showed that the basement was exhumed to the surface prior to the onset of Permian deposition on the glacial landscape and was then reburied to a depth of 1 km or more during Mesozoic times prior to Cenozoic exhumation.

Green et al. [22] reviewed evidence from a number of other locations in Australia where LTT data and/or landscape analysis revealed episodes of burial and exhumation, often in areas previously thought to have been stable over 100s of Myr. Examples include the Davenport Ranges, Northern Territory [153] and Central Australia [154].

6.2. The Southern Africa Supercraton

As reviewed by Kohn and Gleadow [20], numerous LTT studies of southern Africa have been carried out, largely aimed at investigating the evolution of the distinctive landscape of the region. These studies focussed primarily on defining exhumation histories, with a prevailing view that the region was buried by additional thicknesses of upper Carboniferous—Lower Jurassic sediments of the Karoo Basin prior to the onset of Cretaceous exhumation [155]. In contrast, Green et al. [156] showed that, at least along the southern margin, a first phase of exhumation must have been complete before deposition of the Upper Jurassic—Lower Cretaceous Uitenhage Group sediments, much of which was again removed Late Cretaceous exhumation.

Studies along the Atlantic margin of Namibia have reported km-scale mid- to Late Cretaceous exhumation [157–160]. The nature of the rock removed was not specifically considered in most of these studies. However, the presence of Jurassic sandstones and Lower Cretaceous volcanics at outcrop, overlying the sampled units, shows that much of the rock removed during Cretaceous exhumation had accumulated after the deposition of these sedimentary and volcanic remnants, as adopted by [161].

Green et al. [29] reported AFTA data from basement forming a late Carboniferous—early Permian glacial landscape in northwest Namibia (Figure 13). Upper Carboniferous—lower Permian Dwyka Group sediments rest on the basement surface and are overlain by Lower Cretaceous Etendeka basalts. Results showed that the basement was exhumed from >110 °C to the surface in the late Carboniferous and then, together with the Dwyka Group sediments, reburied to 80–90 °C and exhumed close to the surface once more prior to deposition of the Etendeka basalts. One or possible two phases of burial and exhumation followed.

Green and Machado [162] reported AFTA data in samples of Precambrian basement and overlying Maastrichtian–Campanian sandstones from the coastal plain of the Namibe margin of Angola. Results defined a series of cooling episodes, both before and after deposition of the Cretaceous deposits, defining a history involving multiple episodes of burial and exhumation. Adopting a similar approach considering geological constraints, da Silva et al. [163] reached similar conclusions.

6.3. Discussion

The studies discussed above all define histories involving repeated episodes of burial and exhumation of cratonic regions, despite their different tectonic and geographic settings. This consistency suggests that such episodic vertical movements define a general characteristic of craton behaviour. LTT data from a number of other cratonic regions also display evidence of Phanerozoic km-scale exhumation, e.g. North China Craton [164] and the Dharwar Craton of the eastern Indian peninsula [165]. Furthermore, marine Danian sediments of the Deccan traps overlying the Dharwar Craton on the western Indian peninsula are now at an elevation of c. 600 m [166], and inverse modelling of drainage networks suggests Neogene tilting of peninsula India [167], where elevated plateaus dominate the landscape [168]. Based on these observations and on the results presented here, we suggest that these cratonic regions have also undergone histories involving episodic burial and exhumation.

We should emphasise that such behaviour is not restricted to cratonic regions but has been observed in a wide variety of geological settings, including intracontinental platforms, sedimentary basins and passive continental margins [22, 169]. This behaviour has important implications for the nature of tectonic processes, as we discuss later (Section 8).

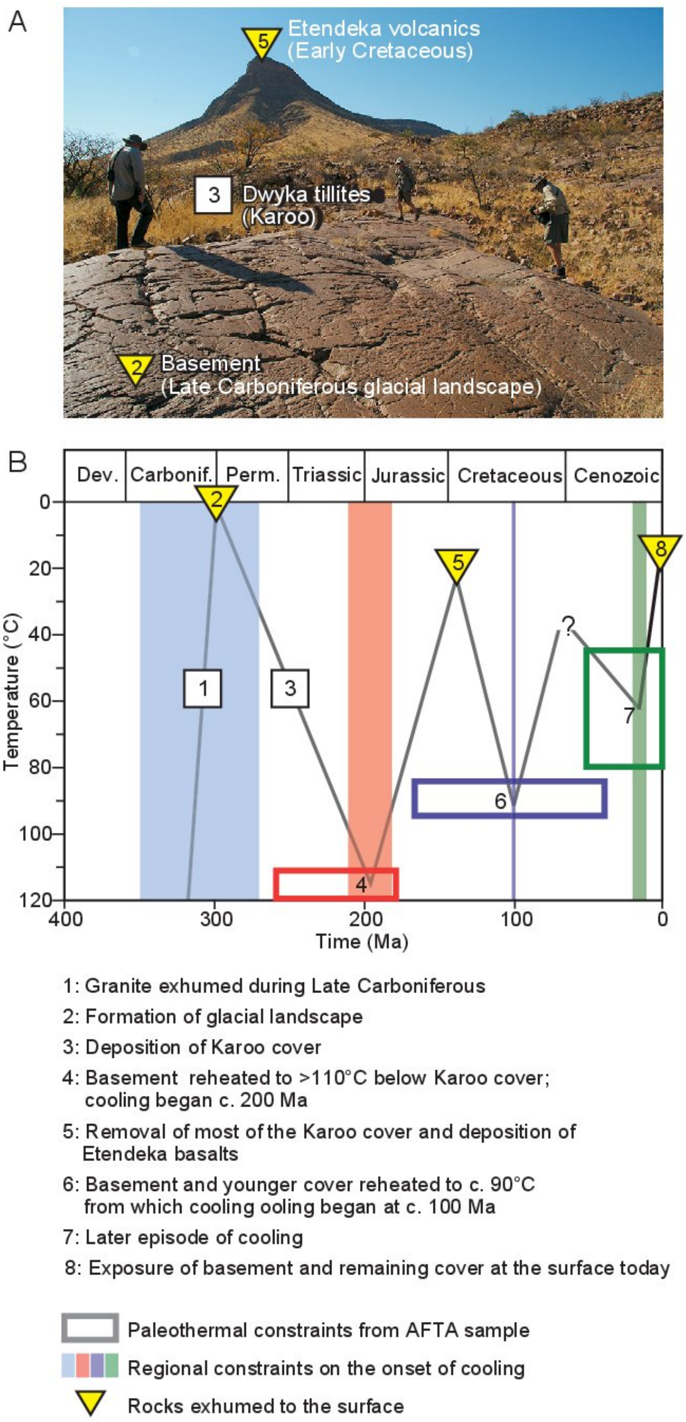

Figure 13. Stratigraphic constraints on the thermal history interpretation of AFTA data from a basement outcrop in northwest Namibia (18.184 °S, 12.762 °E) [29]. (**A**) Late Carboniferous—early Permian glacial landscape, as evidenced by the roche moutonnée on which the geologists are standing, which is actively being exhumed from beneath a former cover of the late Carboniferous—early Permian Dwyka Group of the Karoo Supergroup. This is overlain, in turn, by basalts of the Lower Cretaceous Etendeka volcanics, comprising the distant peak. (**B**) Extraction of thermal history information from AFTA data in apatites from the granite of the roche moutonnee reveals three episodes of cooling, as shown by the coloured box outlines (4, 6 and 7). AFTA data from samples across the region provide constraints on the onset of four episodes of cooling/exhumation, as shown by the vertical, coloured bands. Integration of AFTA with stratigraphic constraints defines the episodic nature of the thermal history. Interpretation of the AFTA data in terms of monotonic cooling clearly conflicts with geological evidence at this location. Note that if erosion had been more pronounced, and the cover rocks removed, as over a large area of the surrounding country, no evidence would be preserved of this episodic heating/cooling history.

7. Why is the Instability of Cratons not Widely Accepted?

Situations where the presence of sedimentary deposits on cratons and their relation to denudation surfaces provide direct evidence of episodes of subsidence/burial and uplift/exhumation (Figure 3) have been recognised for many decades [25, 170], as have the stratigraphic arguments presented by Sloss [150]. More recently, LTT studies have provided further documentation for the vertical movements of cratons, as reviewed above. However, this wealth of evidence for the episodic burial and exhumation of cratons and other basement regions does not seem to have had wide impact on the understanding of cratonic behaviour in terms of vertical movements. It is therefore worth asking why this behaviour is not more generally recognised within the geological community.

7.1. Stratigraphic Gaps Assumed to Represent Tectonic Stability Despite Evidence to the Contrary

As geology is based primarily on the study of the rock record, it seems that exposure of Precambrian basement rocks over wide areas with (limited or) no Phanerozoic sedimentary cover has led many to assume that no other rock was ever deposited. Thus, this configuration must represent Phanerozoic tectonic stability—even though evidence to the contrary is often available. As discussed in the Introduction, the meaning of 'cratonic stability' is often not specified but typically refers to the old age of the Precambrian lithosphere forming the coherent blocks of cratons. Many studies focussed on cratons are thus not concerned with whether cratons are stable in terms of vertical motion and pay no attention to available evidence for such instability [5, 14, 15].

The tendency to consider gaps in the geological record as the result of tectonic stability is seen in many parts of the world, where familiarity with the preserved geological record has led to a resistance to accepting that any rock units that are not present today were ever deposited. Green et al. [22] quoted examples from south-eastern Australia [171], UK [172, 173], Brazil [174, 175] and Fennoscandia [8, 13]. Others have interpreted gaps in the stratigraphic record as representing time intervals during which non-deposition and/or surface uplift and erosion occurred [176] and thus *a priori* discarding the possibility that burial followed by exhumation may have taken place during such intervals.

But, as emphasised by Ager [21], to fully understand geological evolution it is necessary to consider carefully what happened during these gaps in the preserved rock record. Simply assuming that nothing happened and that the gaps represent stability cannot be regarded as objective reasoning, particularly in the face of evidence to the contrary.

7.2. Lack of Mechanism(s)

In part, resistance to the idea of the former presence of rock sequences that are no longer present stems from the lack of an accepted mechanism by which such cover units could have been deposited and removed. Green et al. [22] suggested that one reason for this is that no realistic attempt has been made to produce one. They supported this suggestion by quoting Molnar [177] - '*.. geophysicists have a tradition of rejecting hypothesized processes on the grounds that they cannot happen, when not all underlying processes are known*'. But it also illustrates a conservative nature to explaining geological phenomena which is not conducive to revealing previously unknown processes. This experience has many parallels with negative attitudes to theories of continental drift and plate tectonics despite abundant evidence in support of these theories [178].

7.3. Different Approaches to Extracting Thermal Histories from LTT

Many LTT studies over the last 20 years or so have been based on the tandem application of AFT and AHe dating to extract thermal history information and histories of exhumation (Section 2.1). This is problematic because the diffusion models used to extract thermal history information from AHe data do not accurately reproduce geological behaviour [179]. This problem has been brought into focus recently by studies of He diffusion based on ramp-heating experiments [180, 181], documenting that few natural apatites show patterns of He-loss characteristic of simple diffusive processes. This observation, which explains why AHe data do not show the expected correlations with equivalent uranium content and grain size, suggests that the results of all studies based on such models cannot be considered reliable. AHe ages similar to or greater than AFT ages in the same sample therefore cannot be explained by the effects of radiation damage, as is commonly the case. The combination of both methods to determine thermal histories will inevitably require artificially lower temperatures during the most recent history in outcrop samples.

Studies based on AFT data alone can also produce misleading results. Hestnes et al. [182] presented a re-evaluation of AFTA data from Green et al. [48] in a vertical sample transect from the Jotunheimen mountain in western Norway, concluding that their analysis was inconsistent with the episodic heating and cooling history proposed by Green et al. [48]. However, Figure 9 of Hestnes et al. [182] shows that their history is broadly consistent with the constraints provided by Green et al. [48]. In this regard their work can be viewed as validating the Green et al. [48] interpretation. A key difference between the two studies is that Hestnes et al. [182] attempted to define thermal histories based on all data from the vertical transect, over an interval of 2 km, whereas Green et al. [48] extracted solutions from individual samples independently. As discussed in Section 4.3, deeper samples (or samples at lower elevations in this case) were at sufficiently high temperatures in the earlier part of the history, that no fission tracks were retained until later cooling episodes. Thus, data in these samples cannot be used to define earlier episodes. Defining five cooling episodes in all samples over an elevation range of 2 km is beyond the capabilities of the method, although Hestnes et al. [182] appear to have come close in their Figure 9j. While this example is not from a cratonic terrain *per se,* the principles involved apply generally.

A more basic factor, particularly in early studies, was a focus on basement terrains devoid of sedimentary cover (or in some cases ignoring it), allowing histories of continuous cooling.

7.4. Misreading Evidence from Regional Landscapes

François et al. [7] argued that primary observed cratonic features, such as their flat topography and 'frozen' heterogeneous crustal structure, are keys for understanding of craton longevity. They argued that the lithosphere has to be strong enough to keep density heterogeneities frozen through time without developing major gravitational instabilities and topographic undulations. The authors thus assumed that the 'flat topography' (peneplains?) represented craton stability, rather than examining the features of the regional landscape relative to the stratigraphic record (Section 2.2) to investigate the specific denudation history of a given region.

François et al. [7] suggested that one key characteristic of cratons had been neglected: that '*the central zones of cratons generally have a smooth topography, which remained largely unchanged ...., sometimes over very long periods of time (>200 Myr)*'. They referenced this to Belton et al. [153], but these authors actually provided evidence that the landscape in question has undergone kilometre-scale burial and exhumation within Phanerozoic times and argued against long-term stability. François et al. [7] further claimed that long-term stability was '*attested in the Canadian and Australian craton by the very little amount of sedimentation or erosion of intra-cratonic origin'* with '*sedimentation/erosion of intra-cratonic origin' appearing to be 'very low* <2.5 µm/yr *in average since ca.1.7 Ga'.* This claim was referenced to a study of the Canadian shield by Flowers et al. [183], but a number of later studies have shown that this region has undergone cycles of km-scale burial and exhumation [149, 184].

The age of the rocks that form the building stones of mountains have in many cases been assumed to represent the age when the topography was formed [9, 12]. However, Precambrian rocks of the Guiana Shield were peneplained in the Early Cretaceous and only reached their present elevation after Miocene uplift (Section 3), while Precambrian rocks in East Greenland were raised up to 3 km in the late Neogene (Section 5).

8. Speculation on Mechanisms

Craton-wide unconformities extend from the cratonic interiors to the continental shelf and reflect km-scale epeirogenic movements [19, 150]. Even though this was recognised at the time when the horizontal movements of the continental plates were established as the foundation of geoscience, the vertical movements of the plates away from active collision zones have remained a controversial topic. As discussed in Section 7, the primary causes for this controversy concern the failure to acknowledge the former presence of thick sedimentary covers and the lack of accepted mechanisms capable of producing the episodes of vertical motion of the crust that would allow such cover units to accumulate and subsequently to be removed across regions of continental scale. It is important to appreciate that these episodes of vertical motion affect basement regions and adjacent sedimentary basins [22], the cratonic hinterlands and the continental margins (Figure 10). The resulting unconformities, including erosion surfaces in basement, are often very low angle in nature, reflecting the spatial scale of the affected regions and have therefore often mistakenly been regarded as representing periods of stability.

8.1. Possible Mechanisms Based on Surface Observations

Based on the surface observations summarized in this publication, we suggest that a number of plate-tectonic processes may explain aspects of the episodes of the vertical motion of the continents during deep geological time. Geodynamic modelling is required to test these ideas and to obtain insights into the properties of the earth that allow these recurrent episodes of uplift and subsidence.

One example of the scale of these episodes is the peneplanation of the northern part of South America during the earliest Cretaceous (Neocomian) in response to mantle upwelling and the clockwise rotation of the continent during the opening of the southern South Atlantic, which resulted in compression along the Equatorial margin (Section 3). Our analysis further shows that the subsidence and burial that preceded the episodes of exhumation involved the Guiana Shield as well as the Amazon Basin (Figure 6).

Late Eocene uplift and erosion affected much if not all of Greenland and removed most of the thick post-rift succession that had accumulated after break-up in the North-East Atlantic (Section 5). This episode of exhumation coincided with a minimum in the rate of sea-floor spreading and a significant change in the spreading directions in the North-East Atlantic. Adjustments along the eastern and southern boundary of the European Plate may have caused this change [114, 140], indicating substantial changes in the stress regime in and around the North-East Atlantic. These changes at the southern margin of Europe may have generated forces transmitted across the spreading center north-west of Europe, through the asthenosphere [185, 186]. This case indicates the importance of inter-plate stress, more specifically compression driven by resistance to plate motion [87], which again may be the result of a plate-tectonic chain reaction originating in changes in the relative plate motion far from a location in question [187]. Subsequent to uplift during build-up of stress, release of the stress will lead to subsidence.

Pliocene uplift—amplified by the isostatic response to erosion [188, 189]—raised the continental margins in the North-East Atlantic domain with maximum elevations reached in coastal areas close to Iceland, suggesting support from the Iceland Plume due to outward-flowing asthenosphere extending beneath the conjugate margins of the North-East Atlantic [79]. This may be explained by shear forces evolving at the base of the lithosphere by pressure-driven asthenospheric flow from the Iceland Plume [190–192].

Late Carboniferous, Middle Triassic and mid-Jurassic episodes of exhumation affected Greenland and Fennoscandia (Sections 4 and 5). In previous studies [79, 96], we have suggested that these episodes are related to epeirogenic uplift during the breakup of Pangea [193–195]. Epeirogenic uplift will dominate tectonic activity during the lifespan of a supercontinent as trapped mantle heat accumulates beneath the largely stationary supercontinent, ultimately manifesting as hotspot activity contributory to fragmentation [195, 196]. Epeirogenic subsidence is a largely overlooked aspect of the development of supercontinents, but following our observations, it seems likely that the deflation and subsidence will follow episodes of supercontinent inflation and uplift.

The Maastrichtian exhumation that affected a huge area in the Arctic centered around Greenland (Section 5) likely reflects doming above the Iceland Plume rising below central North Greenland upon its arrival in the upper mantle (c. 68 Ma). This episode preceded the mid-Paleocene impact of the plume at the base of the lithosphere at 62 Ma under Greenland that likely contributed to onset of sea-floor spreading west of Greenland [113, 140]. The lag time between the onset of pre-impact doming and the impact itself and the regional extent of the Maastrichtian unconformity is in agreement with studies of rising plumes [197].

8.2. Search for Singular Mechanisms

Several authors have argued that negative dynamic topography generated by subducting, cold lithospheric slabs or by partial lithospheric delamination triggered by plume underplating can explain phases of subsidence and burial of cratonic regions [17, 198–201]. However, these processes cannot explain the episodic character of burial following exhumation (Figure 8C). Furthermore, Van der Meer et al. [202] found no evidence of subducted slaps below Fennoscandia, southern Africa, the Guiana Shield and most of Greenland, where evidence of both subsidence and uplift is well documented, despite thorough mapping across the entire mantle of positive seismic velocity anomalies interpreted as subducted lithosphere.

Hu et al. [203] showed that large portions of the cratonic lithosphere in South America and Africa experienced significant modifications as demonstrated e.g. by widespread Cretaceous uplift and volcanism and present-day high topography. They suggested that these observations reflect plume-triggered delamination of deep lithospheric roots during the Late Cretaceous—Paleogene, whereas they argued that the lithosphere in these regions had been thermally reestablished since then. However, the focus on such unique phases of exhumation, ignore the evidence for the episodic nature of burial and exhumation; e.g. throughout the Phanerozoic as documented in northern South America [49, 87].

Gernon et al. [204] suggested an additional process that could lead to delamination and exhumation. They observed that kimberlites spanning the past billion years erupted about 30 Myr after continental breakup. They also argued that steep lithosphere–asthenosphere boundaries formed during rifting may generate convective instabilities in the asthenosphere that slowly migrate long distances inboard of rift zones. These instabilities may destabilize or remove the basal tens of kilometres of the cratonic lithosphere, leading to substantial exhumation.

This hypothesis can be compared with the observations presented by Green et al. [156], who identified five Mesozoic–Cenozoic exhumation episodes which affected southernmost Africa. These episodes included an Early Cretaceous phase (beginning between 145 and 130 Ma) coincident with the break-up of the southern South Atlantic at c. 135 Ma [72]. This episode was followed by a mid-Cretaceous phase of exhumation (beginning between 120 and 100 Ma), coincident with a marked shift in the composition of kimberlite melt and evidence of removal of 40 km the lithospheric keel in South Africa [156, 204, 205]. It is thus possible that the process proposed by Gernon et al. [204] may explain the mid-Cretaceous episode of exhumation in southern Africa.

Gernon et al. [206] argued against the prevailing notion of cratons as geologically stable terrains based on a model of coevolution of rifting, escarpment formation and exhumation of craton interiors. However, that model ignored evidence that escarpments at continental margins form post-rift [169], and that the development of the cratonic interiors are decoupled from continental breakup, as we have shown here. The development of cratonic surfaces is episodic rather than evolving, and the 'inferred secular exhumation of otherwise stable cratonic interiors' is not enigmatic as claimed by these authors. Exhumation as well as burial are general characteristics of cratons and other parts of continents, operating both prior to and after continental breakup.

In summary, a variety of processes may be capable of producing the processes discussed here. Serious attention should be devoted to assessing and testing possible models, based on the wealth of data available on their effects.

9. Conclusions

The scarcity of Phanerozoic cover rocks on Precambrian basement across vast areas has led many to consider such shield areas as stable cratons, undergoing only slow denudation and emergence. What meets the eye in such regions is only absence of evidence for what happened during hundreds of millions of years: a hiatus in the geological record and a gap in our understanding of the history of the earth. However, the methods described here provide key insights into what happened during the gaps in the stratigraphic record.

Cratons may be stable in the sense that their deep lithospheric keels to some extent protect them from rifting and magmatic intrusions. However, as we have shown here, cratonic regions experience episodic km-scale subsidence and uplift: Repeated phases of burial leads to preservation of old peneplains below sedimentary covers, while exhumation of these supposedly stable regions leads to re-exposure of old peneplains and to formation of new erosion surfaces. Indeed, many of the regions defined as supercontinents by Pearson et al. [14] contain vast areas where km-thick sedimentary covers are present today, but this evidence for significant subsidence of the supposedly stable cratons, is frequently overlooked.

These episodes of vertical motion affect regions at a continental scale, including cratonic hinterlands and continental margins. The resulting unconformities (including peneplains) have often mistakenly been regarded as representing periods of stability. The vast scale of these movements is also important for understanding how re-exposed older peneplains may appear to be surfaces that have remained exposed since their formation.

We suggest it is time to reject the paradigm of cratonic stability and accept that the continents—including cratons—undergo km-scale positive and negative vertical motions over 100s of million years. Therefore, singular mechanisms cannot explain these observations, rather a variety of lithospheric and sub-lithospheric processes may explain these observations. Geodynamic modelling that honour the observations presented here, is required to test these possibilities.

Where we have presented our arguments for episodic burial and exhumation of cratonic regions, we have often met the argument that Occam's razor tells us to choose the parsimonious solution, that rocks cool through the simplest possible path. In answer to this argument, we will quote Sloss [19]: '*it is nowhere stated that the evolution of cratons and their sedimentary covers need be convenient, comfortable, or capable of rationalization by simplistic hypotheses*'.

Author contribution

P.J.: Writing—original draft, Writing—review & editing, Visualization, Methodology, Conceptualization. P.F.G.: Writing—review & editing, Methodology, Conceptualization. J.M.B.: Writing—review & editing, Visualization, Methodology.

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