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Review
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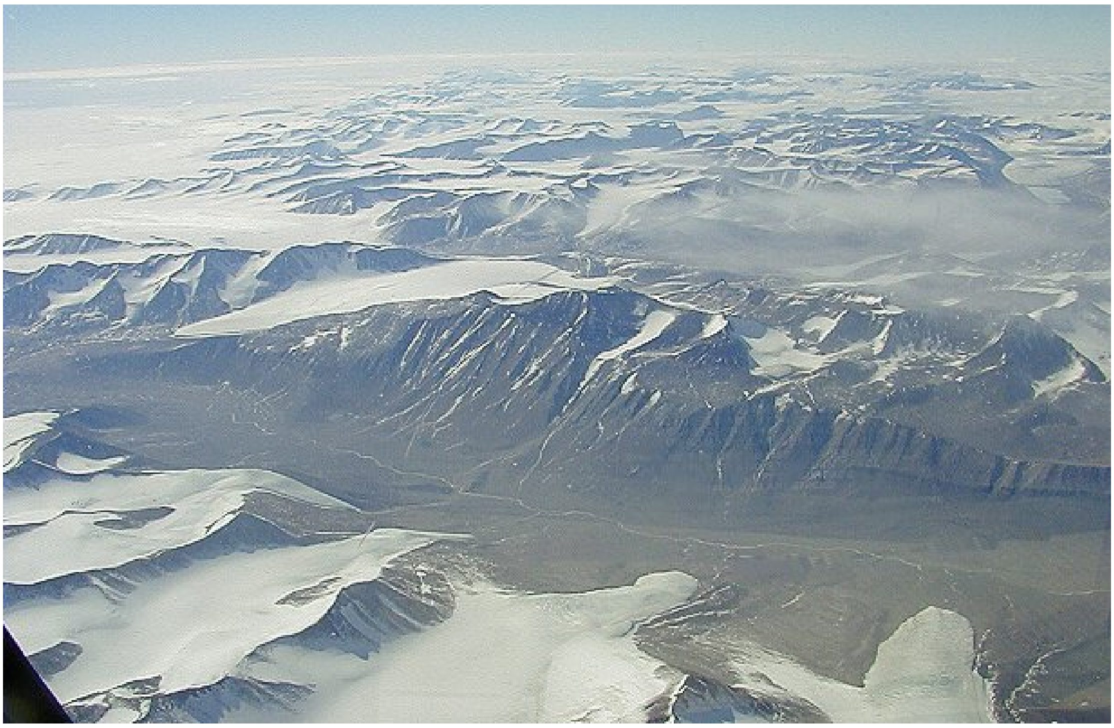
How long have the dry valleys been dry? : A Review on the landscape evolution history of the Dry Valleys, Southern Victoria Land, Antarctica.



How long have the dry valleys been dry: A Review on the landscape evolution history of the Dry Valleys, Southern Victoria Land, Antarctica.

Abstract

The Dry Valleys of Southern Victoria Land, Antarctica make up one of the oldest landscapes on earth. The question of the precise age and mode of landscape formation is essential to the understanding of past East Antarctic Ice Sheet Behaviours. There is evidence from buried desert pavements and in situ volcanic ashfalls that suggest that the dry valleys have remained in a hyper arid polar desert state since the middle Miocene 15 Ma. Contrary to this finding there is evidence from the Sirius Group Diamicts that suggest glaciaition occurred far later than this in the Pliocene (between 3.2 – 2.4 ma). These contradictory findings have created a polarised debate about landscape evolution and past ice sheet behaviours.

1 Introduction

Antarctica contains 90% of the ice on earth, the majority of which is held in the marine West Antarctic and terrestrial East Antarctic Ice Sheets. Through the understanding of past Ice Sheet behaviour, inferences can be made about the stability of the Ice Sheets to present day climate change, a question that is particularly relevant with regard to global issues such as sea level rise. A significant amount of research has been undertaken to try and establish how the East Antarctic Ice Sheet (EAIS) has responded to warmer climatic regimes in the past such as the Pliocene warming 2.9-2.2 Ma when global temperatures are thought to have been warmer than the present day. Until the mid 1980s it had long been assumed that the EAIS had remained stable in a position similar to the present day since the mid Miocene (Shackleton and Kennet 1975). This paradigm was severely challenged by the discovery of Pliocene aged reworked marine diatoms and fossilised *nothofagus* wood in outcrops of diamicts along the Transantarctic Mountains (TAMS) including sites in the dry valleys (including the dry valleys) (TAMs) at high altitudes. This finding suggested that Pliocene warming had caused Ice Sheet deglaciation and subsequent readvance and overriding of the TAMS and a shift from cold-based ice to warm-based ice (Webb 1984).

The Dry Valleys of Southern Victoria land have played a significant role in the understanding of the EAISs past responses to climate change and on the debate surrounding the stability (or deglaciation) of the EAIS. The Dry Valleys are some of the oldest landscapes on earth (Marchant *et. al* 1993 a and b, Denton *et al.*1993, Summerfield *et al.* 1999, Schafer *et al.* 1999). The present day Dry Valleys are characterised by a cold polar desert environment that makes up the largest single ice-free region in Antarctica. The geomorphic history of the region (and other areas along the TAMs where Sirius groups have been identified) have been the subject of intensive scientific research and debate regarding the relative role of processes responsible for their (the Dry Valleys and its morphologies) formation and the timing of these processes. For the Dry Valleys the debate has been centred on the location, age and types of diamicts associated with the Sirius group (Webb *et al*. 1984, Barret *et al*. 1992, Ivy-Ochs *et al.* 1995, Hicock *et al.* 2003), the presence of 15 ma in situ volcanic ash deposits (Marchant *et al*. 1993, 1996), the relative role of weathering processes such as nivation, salt weathering and wind deflation (Selby 1971), mass wasting (Denton *et al.* 1993 Sudgen *et al.*1995 Prentice *et al.* 1998 etc), the relative role and timing of glacier and fluvial processes in the formation of the dry valley geomorphology at macro, meso and micro scales (Denton *et al.* 1993, Sudgen *et al.* 1993, 1995, Prentice *et al.* 1998.) and finally on the dating and investigative techniques that have been used in the aforementioned research

This review aims to bring together the many different areas of research regarding the landscape evolution of the Dry Valleys to assess the relative role and timing of the geomorphic processes responsible for its formation

1.1 Dry Valleys Physical Environment

The Dry Valleys are the largest ice-free region in Antarctica located in Southern Victoria Land between the Ross Embayment and the EAIS (Figure 1). The ice-free region covers an area of 4000km^2. The region is made up of three main transverse valleys the Taylor, Wright and Victoria Valleys (from North to south) (Figure 1). The ranges that separate these valleys are the Asgard and Olympus Ranges. The EAIS drains out two major outlet glaciers either side of the Dry Valley, the Mulock (South) and the Mackay (North).

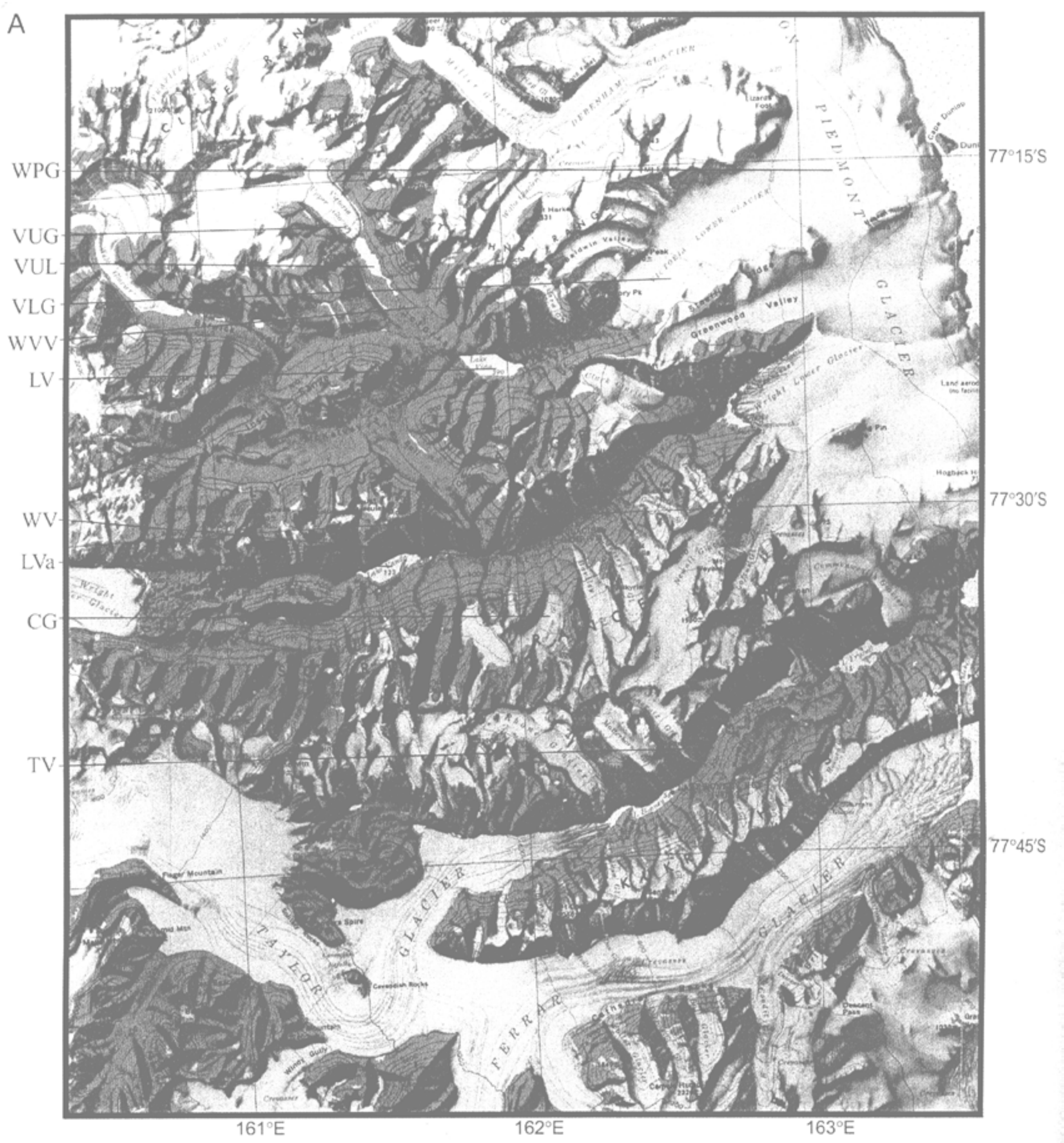


Figure 1 Map of the Dry Valleys of Southern Victoria Land adapted from Kelly et al. 2002

The mean annual temperature on the valley floors (Lake Vanda) is –19.8 °C and the precipitation is around 10cm water equivalent per year (Chinn 1980). Within the Dry valleys there are several large valley glaciers (The Upper and Lower Wright and Victoria Glaciers and the Taylor Glacier) that are fed either by the Taylor dome (Denton 1993), an ice dome that is part of the EAIS, but flows and is fed independent of the main EAIS body. The lower Glaciers (Lower Wright and Victoria) are fed by the Wilson Piedmont located adjacent to the Ross embayment (Figure 1). These glaciers are located in the main transverse valley but many smaller alpine glaciers fill theatre shaped depressions on the valley walls and are fed primarily by wind deposited snow from the polar plateau (EAIS) (Chinn 1980). In the present day hyper arid cold environment the majority of both the valley and alpine glaciers are dry cold based, with the exception of parts of the Taylor Glacier where pressure melting is reached in thick central regions producing wet warm-based basal regions (Chinn 1980). Cold based glaciers have a very limited geomorphic effect on the environment as rock and debris is not readily eroded and entrained without the presence of plucking and abrasion associated with wet warm-based glaciers (Chinn 1980, Denton 1993). Glacier ablation is predominantly driven by sublimation (90 %) and for the greater part of the ice free region sublimation outweighs accumulation by snowfall. High-speed katabatic winds drain of the EAIS down all of the transverse valleys, these winds slow as the reach the lower ends of the valleys toward the Ross Embayment this combined with the prevalence of warmer marine air near the coast produces a moisture gradient.

1.2 The Geology of the Dry Valley

The geology of the Dry Valleys is comprised of a basement complex of lower Palaeozoic igneous and metamorphic rocks overlain by nearly flat lying Devonian to Triassic sandstone, siltstone and conglomerates of the Beacon Supergroup. These rocks are all intruded with the Ferrar dolerites from the Jurassic and Cenozoic age (Barret et al 1992, Marchant et al 1993a). Throughout the higher altitude regions of the Dry Valleys (like other regions of the TAMs) there is Sirius group diamicts such as Mt Feather (Webb *et al.*1984). It is the location and nature of these Sirius diamicts that have been the subject of intense debate relating to the formation and timing of formation of the Dry Valleys and therefore the behaviour of the EAIS.

2 Past East Antarctic Ice Sheet Behaviour (two opposing hypotheses)

Based on geological and geomorphic information two opposing hypotheses have been formed to explain the past behaviours of the EAIS since the mid Miocene. Before a review of geomorphic and geologic research in the Dry Valleys can be completed it is essential to explain the theoretical background about the EAIS past behaviours,

2.1 The Stabilist Hypothesis

As mentioned above up until the mid 1980s it was largely accepted among the scientific community that the EAIS had remained stable since the mid Miocene around 14 ma (Bull 1962, Selby 1971, Shackleton and Kennet 1975 Marhcant *et al.* 1993, 1996, Sudgen *et al*. 1993, et al 1996.). From the interpretation of oxygen isotopes found in ice cores in Antarctica it was found that since 14-15 ma ice EAIS had remained a stable cold based ice sheet and that no unambiguous evidence for significant Pliocene deglaciation of East Antarctica was found (Shackleton and Kennet, 1975, Kennet and Hodell 1993).

2.2 The Deglaciation Hypothesis

During the Pliocene between 2.9 and 2.2 Ma there was a major shift in the earths climatic systems leading to a period with global temperatures warmer than the present day (Shackleton 1993). Based on the identification of Pliocene aged Sirius group diamicts containing marine diatoms and fossilised *nothofagus* wood on many high altitude sites along the TAMs Web *et al.* (1984) and Denton *et al*. (1984) independently concluded that the EAIS has overridden the TAMs (and Dry Valleys) during the Pliocene depositing the diamicts on a site that were forested with *nothofagus* (a setting similar to present day Patagonia). Further to this the marine diatoms found in this diamicts, were argued to have been laid down in open water in East Antarctica like the Pensacola Basin and subsequently stripped and redeposit along the TAMs by and expanding wet based EAIS (Webb *et al*. 1984, Barret *et al.* 1991). This theory has been used to explain the sites in the Dry Valleys such as Table Mountain and Mount Feather where Sirius group deposits are found.

3 Landscape Evolution of the Dry Valleys

Throughout the Dry Valleys there have been many landscape and landforms identified that have interpreted in many ways to add weight to both the deglaciation and stabilist hypotheses. To an extent the polarity of these two contradictory hypotheses has meant that many landforms have had multiple interpretation both in terms of process and timing.

Prior to the discovery of The Mount Feather diamicts the dominant model for landscape evolution of the Dry Valleys was that there had been significant mid Miocene glacial geomorphic activity followed by the onset of hyper arid polar desert conditions. This activity was thought to be mainly produced but wet based outlet glaciation and an expanded EAIS (Bull 1962, 1964). This was based on the valley morphologies, and the large amount of till scattered throughout the valleys. Other dominant processes responsible for the present day morphology included wind deflation, nivation and salt weathering under hyper arid cold desert conditions since around 15ma (Selby 1971). Post Sirius Group discovery a more intensive period of geomorphic and geologic research into the landscape evolution has yielded many differing interpretations of morphologic features and a vast variety of landforms on differing scales, that have been used to interpret the evolution of geomorphic processes and their pertaining climate regimes. This large amount of geomorphic interpretation and the nature of such interpretations are of such a scope that one single review could not cover the body of literature in great detail.

In 1993 a series of authors (Denton et *al.*1993, Marchant *et al.* 1993 a and b and Sudgen et *al.* 1993) used stratigraphic, geomorphic and dating evidence to produce a model of landscape evolution that suggested that whilst wet based glaciation had occurred in late Miocene (14.4 – 15.2 Ma) this EAIS overriding of the TAMS produced only small scale landforms suggesting that it was not the major geomorphic agent responsible for the macro morphological features present in the Dry Valleys. The majority of the macro scale landforms and bedrock morphologies predated this period of EAIS advance. Instead it was argued that based on the similarities to present-day cueastaform landforms such as in Colorado, the dominant landscape formation process was scarp retreat and embayment propagation under a semi arid environment where fluvial debris transportation played a significant role (Denton et al. 1993). An example of this planation surface cueastaform landscape in the dry valleys includes the valley sides of the Upper Taylor Valley, Wright Valley and the Arena Valley (Figure 2)

Figure 2 Planation surface and cueastaform landforms produced by semi arid backscarp weathering and fluvial transportation (Source: Sugden et al 1995). Note that on the top left is buried desert pavements and to the right is ashfall deposits.

More importantly it was found that no significant landscape evolution occurred in the Asgard Range area after 13.6 Ma. This was based on the identification of *in situ* ashfall deposits dated using $^{40}Ar/^{39}Ar$ techniques. This ash was located both in frost cracked patterned ground and overlying slope colluvium (Figure 3), ventifacts and desert varnish. These findings are significant to the Sirius debate as they demonstrate that since the middle Miocene cold hyper arid conditions have prevailed and little slope evolution (Presence of >13.6 Ma colluvium) has occurred (Marchant et al. 1993).

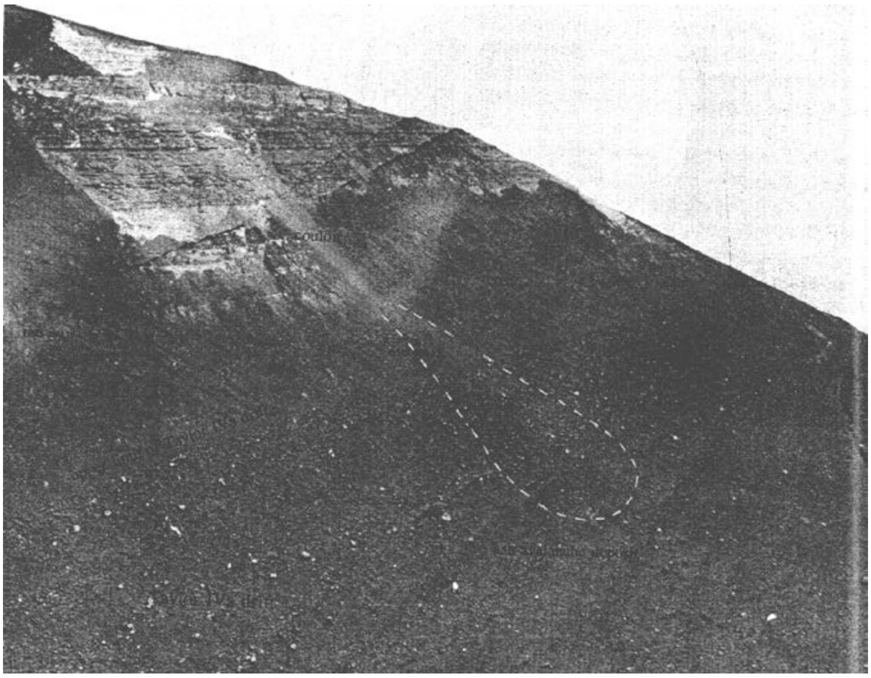


Figure 3: *In Situ* Ashfall covering pre-exiting colluvim indicating stable nonerosive environments in the Asgard Ranges since 13.6 Ma (Source: Marchant *et al.* 1993)

Diamicts and till drifts have been identified in many areas of the Dry Valleys, these drifts that initially were interpreted as part of large-scale glaciation and landscape evolution, have since been argued as small-scale deposition by expanded valley and alpine glaciers from warmer (although not significantly) periods during 2.4 Ma and 15 Ma suggesting that some minor glacial expansion has occurred but no major overriding by the EAIS (Sudgen *et al.* 1993, 1995, Denton *et al.* 1993).
There is still a significant debate regarding the relative role of glacial and fluvial processes and the spatial extent that glaciation has covered under warmer regimes such as the Pliocene. Excluding the Sirius paradox for the evolution model much of the literature has shifted to a semiarid macro fluvial geomorphic agent as the

dominate process with subsequent modifications by wind deflation, nivation, salt weathering and Two significant glacial advances (Not EAIS) both prior to the deposition of ash in the mid Miocene and in the Pliocene under cold desert conditions. However, Prentice et al (1998) have argued that glaciation has had a more significant effect on the landscape. They identified three glacial erosion landscapes based on the altitude of the glacially inferred landforms. Based on geomorphic mapping they identified asymmetric moulding of paired tributary-valley corners on spurs at intersections of trunk valleys, parabolic transverse profiles and longitudinal over-deepening downslope have been interpreted as glacial in origin. These findings are similar to those of Bull et *al.* (1962). These meso-scale landforms are found at three distinct altitudinal bands suggesting that three separate and incrementally smaller glacaitions are responsible for the landscapes present today. They argue that the low (100-600m) and intermediate (1100-1300m) phases of glaciaiton were produced by Overriding by the EAIS, and the High (1300-1900m) was produced by expanded wet based tributary and trunk glaciers. They argue that glaciation much have predated 9 ± 1.5 Ma based on $^{87}Sr/^{86}Sr$ composition of *a* shell fragment found in a glaciomarine diamicts from the eastern Lake Vanda basin (Prentice *et al.* 1993). Of all the geomorphic interpretations of the Dry Valleys this appears to be the least convincing, with little regard for the wide body of literature existing and little or no dating and stratigraphic data used in the interpretation.

3.1 Sirius and wet-based EAIS the deglaciation paradox

The current mid Miocene model for landscape formation followed by the onset of cold desert conditions is complicated by the occurrences of Sirius group Pliocene diamicts high up on Mt Feather and Table Mountain. Barrret *et al.* (1992) suggested that evidence from the Sirius group indicated that the most recent deglaciaton of the ice sheet occurred 3 ma based on diatom assemblages present in the diamicts. Wilson *et al.* (2002) also found that the Sirius diamicts from Mount Feather were formed under wet-based glacial deposition from outlet glaciers fed by the EAIS. This finding was based of data from stratigraphic, sedimentological, mircromorphologic and petrographic analysis of shallow cores. They noted that most of the sampled diamict was local in origin but the diatoms assemblages were more distal in origin

(Wilson et al. 2002). Based on the diatomic assemblages Wilson et al (2002) suggested that more temperate climatic conditions persisted in the mount feather region until at least the late Miocene early Pliocene contrary to ash deposits dates (Marchant *et al.* 1993). In recent years through the improvement in dating techniques better data about the Mount Feather, suggesting that cold desert condtions may well have prevailed after 15 Ma.

Hicock et al. 2003 used new ice flow direction analysis techniques and tillite geometry to analyse the Mount Feather Sirius Group diamicts. They found that the diamicts where accumulated beneath a wet based ice (striations, faceting, rotation and till formation and characteristics) on transverse paleovalley floors noting that this feature was a hanging valley remnant that had been largely removed by subsequent erosion. Their findings also indicated that the diamict was formed primary by lodgement as part of an ancient outlet glacier that had been located 1500m lower than its present day position near the summit of mount feather. Based on calculated uplift rates of 100m/m.y. derived from apatite fission tracking (Fitzgerald 1992) they inferred that the Sirius diamict located on Mount Feather was at least 20 Ma. These findings provide a more plausible age estimate for the Sirius diamict that allows for the onset of cold desert conditions after 15 Ma, which may solve the Mt Feather Sirius group paradox. These data are also backed up by cosmogenic noble gas studies that found ages of 10 Ma for the Mt Feather diamict (Schafer *et al.* 1999) these figures were minimum ages that did not take into account uplift and erosion, and suggested that the actual age was closer to 20 Ma around the time that the drake passage separated from Antarctica and circumpolar currant formed.

4 Conclusion

The Landscape evolution history of the Dry Valleys is complex and understanding the timing and processes responsible for the geomorphology is essential not only for local paleoreconstruction but also for the understanding of past EAIS behaviours under changing climatic regimes. From this review the most likely chronology of landscape evolution based on the main literature body suggests that cold desert conditions similar to those found today in the dry valleys began at least 15 Ma. Fluvial weathering may have been the most significant geomorphic agent on a macro-scale but it is clear that mid Miocene wet based glaciation from the EAIS and subsequent valley and alpine glacier expansion has played a significant role in the formation of landscapes. From the research at present it seems that for the Dry Valleys the Sirius Paradox seems to be solved but with the improvements in dating and analysis techniques future research may tend back towards the Pliocene deglaciation hypothesis.

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