

Transport of the Stonehenge Bluestones: Testing the Glacial Hypothesis

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Introduction

IN 1923 THOMAS PUBLISHED his seminal paper on the provenance of the Stonehenge 'bluestones' and, in unequivocally attributing the majority of them to source outcrops in the Preseli Hills of Pembrokeshire, highlighted the improbability that the stones could have been transported to Salisbury Plain by ice (Fig. 1), an hypothesis suggested earlier by Judd (1902). This led Thomas to invoke human transport, either overland or by a combined sea/overland route, from Preseli to Stonehenge, an explanation which has subsequently become widely accepted by both the archaeological and geological fraternities: 'There can be no question of the stones having been carried even part of the way towards southern England by ice during the Pleistocene period, and their appearance at Stonehenge can only be explained as the result of deliberate transport by man' (Atkinson 1979, 105).

In 1971, however, Kellaway highlighted a body of evidence pertaining to possible glaciation of southern England unavailable to Thomas in the 1920s, and in doing so explicitly supported Judd's earlier contention that the Stonehenge 'bluestones' were glacial clasts transported from Preseli by ice and subsequently used by prehistoric man in the construction of the monolith. In a series of later papers, Kellaway (Kellaway *et al.* 1971, 1975; Hawkins and Kellaway 1971) developed this model further, claiming extensive glaciation of not only southern England, but also of the Celtic Sea and English Channel. Despite widespread criticism of this model in the 1970s, Kellaway has recently revived the glacial hypothesis (1991a, 1991b), albeit in slightly altered form, and his earlier ideas have been invoked by another group advocating glacial transport (Thorpe *et al.* 1991). The glacial hypothesis is therefore very far from having been convincingly falsified, and for a significant minority it remains the favoured explanation: 'There is infinitely more evidence to

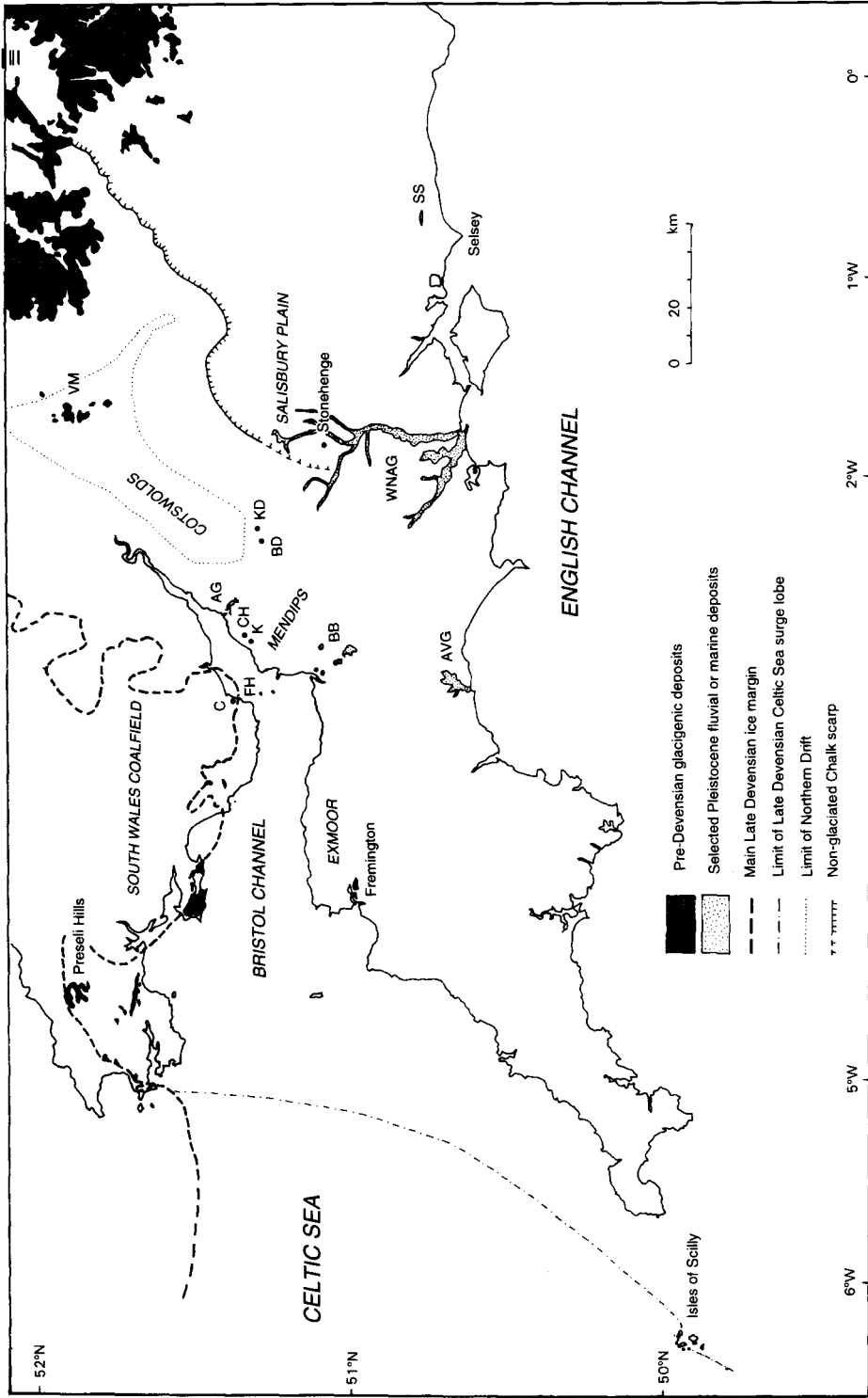


Figure 1. Location map showing sites mentioned in the text. C – Cardiff; FH – Flatholm; AG – Avon Gorge; CH – Court Hill; K – Kenn; BB – Burtle Beds; AVG – Axe Valley gravels; BD – Bathampton Down; KG – Kings Down; WY – Wyllye, Nadder and Avon gravels; SS – Slindon Sands; VM – Vale of Moreton.

support the theory of ice transport than there is support for the great contemporary myth of long-distance haulage by the Beaker people' (John 1984, 38).

The Stonehenge 'bluestones' and their source

'Bluestone' is a 'bag' term to describe all the non-local rock lithologies found in and around the stone settings at Stonehenge. The term is thought to have arisen as a means of distinguishing between the lighter-coloured sarsen 'greywethers' which have a demonstrably local origin as Tertiary silcrete (Thorpe *et al.* 1991), and the more far-travelled stones which generally have a darker appearance (Fig. 2). The major bluestones total in number around 80 (Atkinson 1979), but excavations since the early nineteenth century have recovered a very large number of bluestone fragments from in and around the site (Cunnington 1824; Maskelyne 1878; Judd 1902; Thomas 1923; Thorpe *et al.* 1991). It is now widely accepted, following the detailed petrological investigations of the larger bluestones and fragments by Judd (1902), Thomas (1921, 1923) and Thorpe *et al.* (1991), that four main lithologies are represented at the site.

The most common of these is a distinctive spotted dolerite (formerly termed 'diabase'), the 'spotting' representing white or light-coloured feldspar phenocrysts; some of the dolerites are, however, unspotted. Other igneous rocks include banded rhyolite/ignimbrite and some pyroclastic varieties, whilst the Altar Stone (Fig. 2) and one fragment (Thorpe *et al.* 1991) are pale green micaceous sandstone. Clearly it is critical that the sources of these lithologies can be located with some confidence as this informs any debate as to the means of their transport to Stonehenge.

Ramsey (in Ramsey *et al.* 1858) first suggested that some of the Stonehenge bluestones might derive from a source in the Lower Silurian of north Pembrokeshire, but he mentioned other possibilities including North Wales. Though Judd (1902) provided accurate petrological descriptions of the rock types represented, he remained agnostic as to any possible source. Thomas (1921, 1923) was the first to identify possible source outcrops with confidence. He attributed the pale green micaceous sandstone of the Altar Stone to the Old Red Sandstone of either the Senni Beds (Glamorgan) or the Cosheston Group (Pembrokeshire). He supported Ramsey's attribution of the spotted diabases to northern Pembrokeshire, and identified a source for the banded rhyolites at Carn Alw in the Preseli Hills. All three main bluestone lithologies he therefore attributed to Pembrokeshire, and all igneous varieties to a specific district at the eastern end of the Preseli Hills.

In their recent comprehensive petrological and geochemical analysis of the bluestone materials, Thorpe *et al.* (1991) have refined still further the provenance of the spotted dolerites to three sources in a small area in the eastern Preseli Hills (Fig. 3). They also attribute the rhyolites to four sources within the Preseli district and other (unidentified) locations in Pembrokeshire, and the Altar Stone and sandstone fragment to two locations within the Palaeozoic of south-west Wales. There is therefore strong evidence from all the petrological

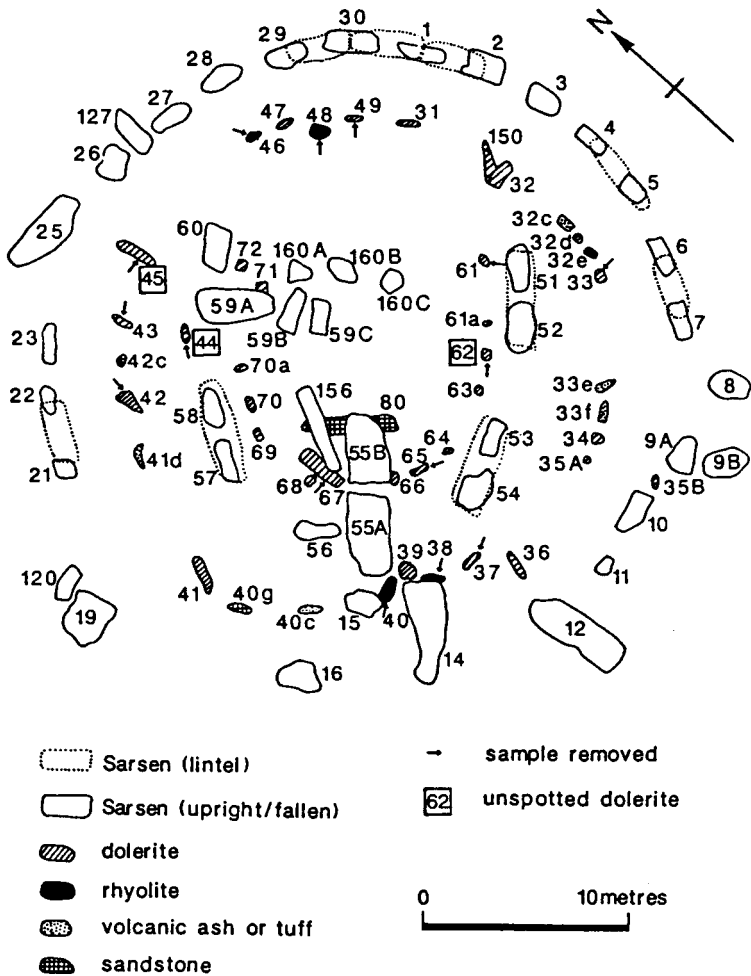


Figure 2. Plan of the central stone settings at Stonehenge from Thorpe *et al.* (1991, fig. 1), after Newall (1959), Chippindale (1987) and Atkinson (1979), showing the petrology of the stones and stone locations. All dolerites are spotted except stones 44, 45 and 62. The Altar Stone is number 80. Stone numbering follows Atkinson (1979) and Thorpe *et al.* (1991). (Copyright: the Prehistoric Society.)

investigations undertaken for a Preseli origin for the igneous bluestones, and a wider Pembrokeshire source for the sandstones and possibly some of the rhyolites. Though the banded rhyolites/ignimbrites could potentially come from a variety of other localities far from Pembrokeshire, the assemblage of bluestone lithologies can be found together within a relatively small area of south-west Wales lending further support to this as the likely source area. Apart from some further discussion on the provenance of the banded rhyolites/ignimbrites in relation to glacial flow lines (see below), for the remainder of this paper it will be assumed that Pembrokeshire, and specifically the Preseli Hills, is the bluestone source.

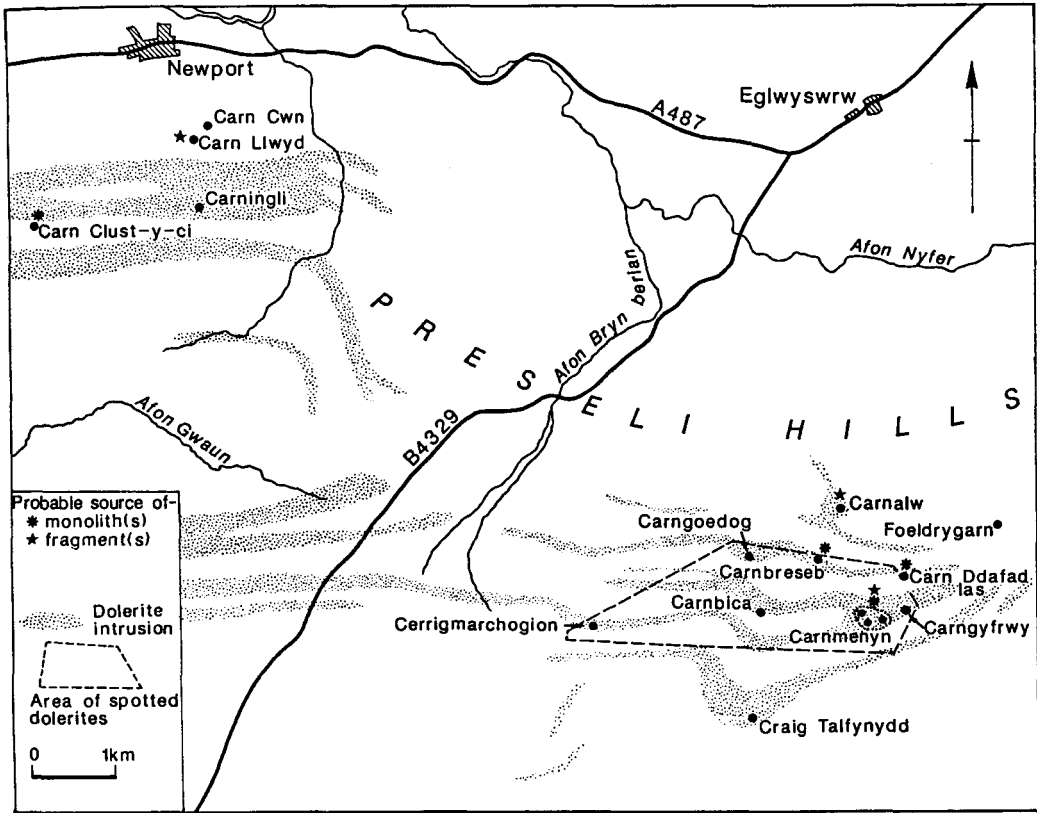


Figure 3. Map of the Preseli Hills showing location of important outcrops of spotted dolerites representing sources for the Stonehenge monoliths and fragments, from Thorpe *et al.* (1991, fig. 8). The three outcrops surrounded by a dotted line are all part of the Carnmenyn outcrop. Approximate extent of the dolerites after Evans (1945). Map base is after Evans (*op. cit.*) and Bevins *et al.* (1989). (Copyright: the Prehistoric Society.)

The purpose of this paper is to review critically the glacial hypothesis for the transport of the Stonehenge bluestones from their source in Preseli to Salisbury Plain. Despite the apparent intractability of this problem, the hypothesis can be tested with reference to existing published observational and modelling data from a variety of sources. To the glaciologist or glacial geologist faced with this problem there are four main questions requiring positive answers if the hypothesis is to remain unfalsified:

- 1 Are glaciers capable of transporting clasts of the mass of the Stonehenge bluestones over the 213 km required?
- 2 Do any undressed bluestone clasts demonstrate morphological and/or surface microwear features consistent with clasts from modern glacial environments?
- 3 Is there any stratigraphical and/or geomorphological evidence to support the contention that Salisbury Plain has been glaciated?

4 Are there other ice flow indicators between Preseli and Wiltshire consistent with this proposed flow trajectory, and, given the regional evidence for glaciation, is such a trajectory consistent with the physics of ice movement?

After reviewing the evidence cited in support of the glacial hypothesis, the paper will address each of these questions in turn, with particular attention given to the two most recent expositions of the glacial hypothesis (Thorpe *et al.* 1991; Kellaway 1991a, 1991b).

The glacial hypothesis: a review

Judd (1902) was the first to suggest that the non-local (bluestone) lithologies found in and around Stonehenge might have been transported by ice to Salisbury Plain. Though he was not specific as to their sources, Judd was impressed by the diversity of lithologies represented, and suggested that prior to weathering on site this diversity had probably been greater: ‘. . . the “bluestones” now remaining at Stonehenge probably represent only the hardest and most durable of the materials employed, many stones of soft and fissile character having disappeared entirely, owing to the action of the weather and the assaults of the relic-mongers . . .’ (op. cit., 115–16). This diverse assemblage suggested to him a similarity with glacial drifts in other districts, though he recognised that the ‘southern limit of boulder clay’ was usually placed by geologists ‘well to the north of Wiltshire’ (op. cit., 117). He cited the fact that scattered boulders often occur well to the south of this limit, and that the ‘sheets of boulder clay which now cover so large a part of the country are merely relics of a formerly much more widely spread formation’ (op. cit., 117). He claimed that the gravels of the rivers draining Salisbury Plain contain many foreign rocks derived from the formerly more widely distributed glacial deposits. Other foreign material he suggested had been removed for incorporation into more recent constructions.

Judd was also impressed by the copious bluestone fragments found in and around the Stonehenge site when compared with the sparse representation of the local sarsen material in the same contexts. This convinced him that the bluestones were dressed, and hence reduced in volume and mass, on site, and that this argues against the stones having been transported by man: ‘The comparative paucity of fragments of sarsen-stone . . . points to the conclusion that these large monoliths were selected for their size and shape, and then rudely trimmed *at the spots where they were found*’ (Judd’s italics, p. 115). As for the bluestones, ‘. . . it is no less obvious that they were for the most part chipped into the required forms and dressed *near the place of their erection*’ (Judd’s italics, p. 115).

Many of the essential points raised by Judd in this first exposition of the glacial hypothesis are repeated in later versions. These include the diversity of the lithological assemblage, the suggestion of former extensive glaciation of the Wiltshire Downs now only represented by *remanié* boulders many of which have been removed since the construction of Stonehenge, and the glacial source for the far-travelled material contained

in the river gravels draining the Wiltshire Downs. Subsequent versions also emphasise the quantity of bluestone fragments discovered on site, and draw the conclusion that the undressed bluestones are therefore unlikely to have been transported by man.

Thomas (1923) critically reviewed Judd's hypothesis and found it wanting: '... there is no evidence of glacial drift on Salisbury Plain as would of necessity have been left by any ice-sheet capable of transporting the masses of rock in question' (op. cit., 252). He argued that '... there is the clearest evidence that ... the ice-front lay only just south of the present coast-line of Pembrokeshire, and that ice as a solid mass never crossed the Bristol Channel to Devon and Cornwall ...' (op. cit., 252). He accepted that ice crossed Pembrokeshire in a south-easterly direction as a lobe of the Irish Sea ice-sheet but that '... the front of this ice-sheet never reached across or far up the Bristol Channel' (op. cit., 254). In thus rejecting the glacial hypothesis Thomas famously raised in detail possible mechanisms of human transport.

Thomas' arguments against the glacial hypothesis and in favour of human transport proved influential, and it was not until 1971 that the glacial hypothesis was revived by Kellaway. Immediately prior to publication of this paper, Kellaway had become aware of new evidence pertaining to the glaciation of southern England, in particular the discovery of impressive glacial sequences at Court Hill and Kenn near Clevedon in north Somerset during the construction of the M5 motorway (Hawkins and Kellaway 1971). Supported by other evidence from South Wales, these data led Kellaway (1971) to speculate that the bluestones were transported to Stonehenge during the 'Anglian' glaciation (Table 1) from Pembrokeshire in west-east flowing ice which entered the Somerset lowlands from the Bristol Channel and continued eastwards to Salisbury Plain (Fig. 4). He distinguished this from a later Wolstonian glaciation (Table 1) which was more limited in extent and represented by the new sites in and adjacent to the Somerset lowlands.

Apart from the glacial sequences exposed at Court Hill and Kenn near Clevedon, Hawkins and Kellaway (1971) also identified other evidence of glaciation, including possible glaciofluvial meltwater channels (Avon Gorge, Rickford Coombe, Limpley Stoke) and the occurrence of far-travelled pebbles on hilltops in the Bristol-Bath district (Bathampton Down, Kingsdown). These high-level gravels were interpreted as glacial in origin, and in another paper (Kellaway *et al.* 1971) the steepening and subsequent cambering of slopes in the same area were attributed to glacial erosion: '... the effect of glaciation has been to produce abnormally steep slopes either by direct glacial action or erosion by meltwater of rocks which may at some time have been frozen' (op. cit., 26).

In his 1971 paper Kellaway speculated that during the 'Anglian' the '... great flow of ice which passed over Pembrokeshire was constricted as it moved up channel, confined on the north by the high ground of the South Wales Coalfield, and on the south by Exmoor and the Brendon Hills' (op. cit., 30; Fig. 4). This glaciation was also said to be responsible for the deposition of the Plateau Gravel or Northern Drift of the Cotswolds and north Oxfordshire (Sandford 1926), an interpretation repeated in Kellaway *et al.* (1971):

Table 1. Summary of Quaternary stage names, ages and correlation with deep-sea oxygen isotope record. Adapted from Bridgland (1994)

Age (in thousands of years)	UK stage names (NW European equivalents in parentheses)	^{18}O stage	Climatic status
10	Holocene or Flandrian	1	temperate
18 —Last Glacial Maximum (LGM)	Late Devensian (Late Weichselian)	2	cold
26	Middle Devensian (Middle Weichselian)	3/4	boreal- cold
71	Early Devensian (Early Weichselian)	5a–5d	boreal- cold
122	Ipswichian (Eemian)	5e	temperate
128	?Wolstonian (late Saalian)	6	cold
186		7	temperate
245	?Wolstonian (mid Saalian)	8	cold
303		9	temperate
339	?Wolstonian (early Saalian)	10	cold
423	Hoxnian (Holsteinian)	11	temperate
478	Anglian (Elsterian)	12	cold
	Cromerian Complex	13–21	

during the Anglian glaciation the Northern Drift ‘... ice-sheets may have made contact with or diverted other masses of ice moving eastward from Wales and the Bristol Channel’ (op. cit., 25). They suggested that at the maximum of the glaciation ‘... the great Northern Drift ice-sheets extended across Oxfordshire towards the Chilterns and to the south-west across Berkshire as far as the Chalk escarpment’ (op. cit., 25). They review the Chalky Boulder Clay found in the Vale of Moreton (Fig. 1; Bishop 1958) and attribute this, and associated glaciofluvial gravels and glaciolacustrine sediments, to the same event. In this paper Kellaway *et al.* (1971) therefore clearly suggest confluence of the ‘Northern Drift

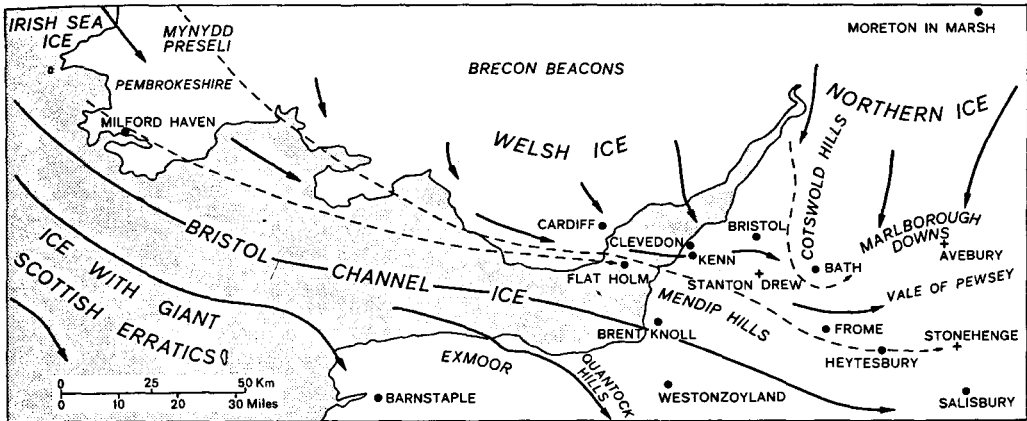


Figure 4. Flow lines of 'Anglian' ice as suggested by Kellaway (1971, fig. 2). Kellaway (1971) suggests that Exmoor might have formed a small centre of ice accumulation, and that the Mendip and Cotswold Hills were overridden at the height of the glaciation. (Reprinted with permission from *Nature*, copyright (1971) Macmillan Magazines Ltd.)

ice-sheet' with a glacier moving eastwards from the Bristol Channel towards Salisbury Plain during the Anglian.

In the 1971 paper Kellaway suggested that the Anglian glaciation also involved extensive glaciation of the Celtic Sea and English Channel causing the emplacement of large erratic boulders on the shore platform of Cornwall, Devon and the Channel coast and the deposition of the Burtle Beds of the Somerset lowlands and the Slindon Sands of Sussex (Fig. 1). This thesis was developed in a later paper (Kellaway *et al.* 1975) in which the flat featureless seabed abutted by cliffines, palaeovalley systems and enclosed deeps of the English Channel were attributed to glacial erosion, though in this review a 'Saale' age was preferred for this extensive glaciation (Table 1). During this event morainic material was said to be deposited at Selsey which caused the impounding of 'Lake Solent', and '... the great mass of ice passed over the Pembrokeshire uplands' and '... being deflected by Exmoor turned eastwards up the Bristol Channel, filled the Somerset lowlands, burying all but the highest parts of the Mendips and filling the gaps leading southwards to the Hampshire Basin and the English Channel coast' (*op. cit.*, 205).

This series of papers therefore postulated extensive Pleistocene glaciation of southern England, the Celtic Sea and the English Channel, including the transport of the Stonehenge bluestones from Pembrokeshire to Salisbury Plain. Though Kellaway's thesis received some limited support from Briggs (1976a, 1976b, 1977), mainly concerning the former distribution of erratics, Kellaway's views were widely criticised during the 1970s, and Briggs' support was itself refuted (Shotton 1976). Green (1973) tested the glacial hypothesis by examining the lithology of Pleistocene gravels in the Wylde, Nadder and Avon valleys (Fig. 1). If Salisbury Plain had been glaciated then these rivers would have

carried the outwash from the glaciers. In 1902 Judd had claimed evidence to support this case. In fact these gravels are composed of materials derived from outcrops within the existing catchments (Chalk flint, Upper Greensand chert and sandstone). Green found small quantities of other ultimately far-travelled lithologies (vein quartz, quartzites, grits, cherts) but these are all present in local Tertiary formations. Unlike the terrace gravels of the undoubtedly glaciated Thames basin, at no point is there a sudden influx of relatively large far-travelled material. Green's conclusion was therefore unequivocal: 'The complete lack of glacially derived material in the Pleistocene river gravels of the Wylye, Nadder and Avon seem to show conclusively that the "Anglian" ice never invaded the basins of these rivers, and that the outwash of the Wolstonian ice was never tributary to them. "Anglian" ice cannot therefore be invoked to explain the presence of large and medium sized Welsh rocks . . . at Stonehenge . . . The problem of the introduction of these rocks to this area remains unsolved' (op. cit., 216).

Aside from the specific instance of Stonehenge, Kellaway's wider views on extensive glaciation, particularly of the English Channel (Kellaway *et al.* 1975), were also criticised. Kidson and Bowen (1976) made the point that 'foreign' boulders are not always evidence of glaciation. Some on the Channel coast have turned out in fact to be very local (Reid 1892) whilst other undoubtedly far-travelled boulders can be attributed to sea-ice or icebergs, or even to ships' ballast. They argue that there are no glacial sediments to support the geomorphological interpretation of former ice, as the Slindon Sands or the gravels of the Hampshire Basin are demonstrably not glaciofluvial in origin. Kidson and Bowen conclude: 'In our view all the facts adduced in favour of glaciation are capable of alternative interpretation. Though they may seem to have some substance collectively, all can be dismissed when examined individually, for deposits may be ambiguous indicators of process and different processes may produce similar landforms' (op. cit., 8).

The essence of Kellaway's (1971) argument, and the criticisms of it during the 1970s, remain relevant because in the most recent investigation of this problem by Thorpe *et al.* (1991) this argument is again given prominence. These authors address the objections originally raised against the glacial hypothesis by Thomas (1923), and argue that these objections are now weaker in the light of subsequent glaciological observations and recent evidence pertaining to glaciation of the critical area between Pembrokeshire and Wiltshire; much of this latter evidence derives directly from the earlier papers of Kellaway. They also emphasise the significance of some early observations by de Luc (1811) concerning the clearance of scattered boulders from Salisbury Plain between 1780 and 1805 (Bartenstein and Fletcher 1987) which they claim supports Judd's (1902) contention of a former widespread cover of glacially transported material across the Wiltshire Downs.

Kellaway has himself recently restated his conviction that the bluestones were transported by ice, but there are significant differences between this new synthesis (1991a, 1991b) and his earlier views. Rather than invoking ingress of ice from the Bristol Channel during the 'Anglian', he now prefers possible transport from a more northerly direction during a Pliocene glaciation at 2.47Ma. He questions the exclusively south-west Welsh

origin for the material and raises the possibility of sources from further north in Wales; particular prominence is accordingly given to a discussion of a boulder of ignimbrite which is similar to Ordovician rocks from Snowdonia. His earlier view that the high-level gravels at Bathampton and Kingsdown (Hawkins and Kellaway 1971) are glacial in origin he reinterprets as Pliocene fluvial or glaciofluvial gravels of the 'Southampton River' (= Solent river; Gibbard and Allen 1994) flowing south-south-eastwards from headwaters in Wales: '... if they [the high-level gravels] have not been glacially transported and deposited (and there is no evidence for this), then they are almost certainly of fluvio-glacial or fluvatile origin ... No ice scratched rocks have been found' (Kellaway 1991a, 225). Meltwater associated with the Pliocene glacial event was '... localized along a route roughly coinciding with the palaeovalley of the Southampton River and this would account for the restriction of Welsh rocks to the Heytesbury-Stonehenge belt' (Kellaway 1991b, 255; Fig. 5). He therefore interprets the bluestones as having been transported down the Solent river in a glaciofluvial context: 'We do not know to what extent the Pliocene glaciation and the penetration of ice carrying the bluestones of Stonehenge affected its [the Solent River] development, but it may well have contributed much meltwater during deglaciation. Much depends on the interpretation of the Stonehenge erratics in the sense that though morainic in origin, they may have been carried for some considerable distance downstream in floating ice' (Kellaway 1991a, 228).

There are therefore significant differences between these two most recent expositions of the glacial hypothesis. Thorpe *et al.* (1991) argue for derivation from Pembrokeshire in a Pleistocene west-east ice flow which draws heavily on Kellaway's earlier ideas (1971; Kellaway *et al.* 1975), whilst Kellaway (1991a, 1991b) questions the Pembrokeshire source and prefers a more northerly glaciation during the Pliocene with the bluestones themselves representing glaciofluvially or river ice transported clasts. Thorpe *et al.* (1991) have themselves drawn this distinction; they comment that a more northerly source is '... inconsistent with the evidence for derivation of Stonehenge bluestone monoliths from Preseli and we propose that these were transported by glacial action through the Bristol Channel' (op. cit., 147–8). Also implicit in the two discussions is a difference in the mode of glacial transport, Thorpe *et al.* (1991) preferring transport of the bluestones as 'free boulders' on the surface of the ice (supraglacial transport) whereas Kellaway (1991a, 1991b) emphasises the significance of striations and faceted surfaces which would imply subglacial abrasion.

Testing the glacial hypothesis

Entrainment and transport of large boulders by glaciers

The largest of the bluestone boulders at Stonehenge has a weight of the order of four tons (Atkinson 1979). There are no natural agencies capable of transporting boulders of this size over the distances required in a single trajectory other than by glacier.

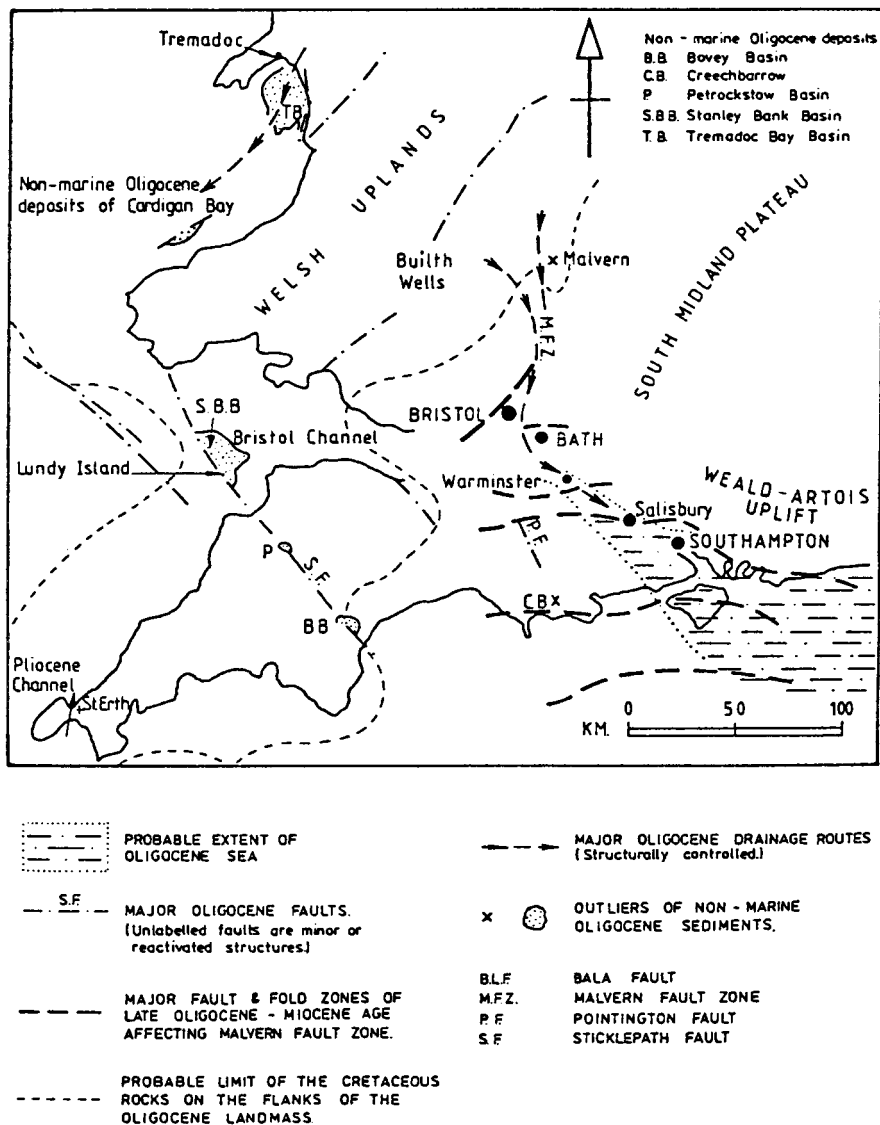


Figure 5. Mid-Tertiary tectonics, relief and sedimentation, from Kellaway (1991a, fig. 13.3). The Pliocene Solent river is suggested to have followed approximately the same route shown for the Oligocene drainage routes. The Stanley Bank Basin offshore Fremington is also shown. (Copyright: Bath City Council.)

Gravity-driven mass movements on slopes and even flood flows in high energy river channels are capable of entraining and transporting particles of this mass but only over very short distances and always exclusively downslope. Thorpe *et al.* (1991) suggest supraglacial entrainment and transport for the Stonehenge bluestones. Citing Flint (1955)

they argue that 'free boulders' derived from nunataks may have dimensions measured in tens of metres and that they can be found tens of kilometres from source. They argue that the Stonehenge bluestones were derived by mass movements from bedrock sources forming nunataks in the Preseli district, and then transported supraglacially the entire distance from Pembrokeshire to Salisbury Plain.

There are many analogous situations described in the glacial geological literature. Glaciers are known to be able to transport individual boulders up to 10^5 tonnes in weight over thousands of kilometres, often irrespective of topographic constraints. Both the mass and trajectory distance of such erratics are orders of magnitude greater than the Stonehenge case. One of the most famous of all glacial erratics is the Big Rock of Okotoks in Alberta, Canada. This large quartzite mass of some 120,000 tonnes is derived from the Jasper area from the west side of the North American continental divide. It is believed to have been dumped from an ice-free peak (nunatak) onto the surface of the Cordilleran ice cap and transported supraglacially east to the foothills near Calgary as part of the Foothills Erratic Train (Stalker 1976). The mode of entrainment and transport of this erratic, and its trajectory over significant topographic features, is similar to that suggested by Thorpe *et al.* (1991) for the emplacement of the Stonehenge bluestones. Though there is a net down-slope gradient of some 250 m between the Preseli source, at around 350 m OD, and Stonehenge, at 102 m OD, the proposed route (Fig. 4) would involve ice flow over topographic features as low as -50 m OD in the Bristol Channel and up to 320 m OD in the Mendips and uplands of north Somerset.

In warm-based situations, where the basal ice is at the pressure melting point, glaciers move by basal sliding and internal deformation (Fig. 6). Where the basal ice is below the pressure melting point it is frozen to the bed and basal sliding is inhibited; in this situation the ice moves by internal deformation alone (Paterson 1981). Internal deformation, or strain (ϵ_s) at a point within the glacier is determined by shear stress (τ) and a constant related to temperature (A; Glen Flow Law; Glen 1955):

$$\epsilon_s = A \tau^n \quad (1)$$

where n is a constant (creep exponent). Strain increases as shear stress and temperature increase. The basal shear stress (τ_b) in turn is described by:

$$\tau_b = \rho_i g h \sin \alpha_s \quad (2)$$

where h is ice thickness, α_s is the gradient of the ice surface, ρ_i is the density of ice and g is gravitational acceleration (Fig. 6). This equation (2) is sometimes known as the 'driving stress' equation (Drewry 1986) since it describes the forces required to induce motion by strain deformation in a glacier. Shear stress increases as ice thickness and gradient increase, so ice flow is controlled not by topographic constraints at the bed but by the slope of the ice surface. It follows that, in situations where indicator erratics have been transported by ice across topographic obstacles, the maximum slope of the ice surface was discordant with bed topography. There are therefore theoretical grounds to explain

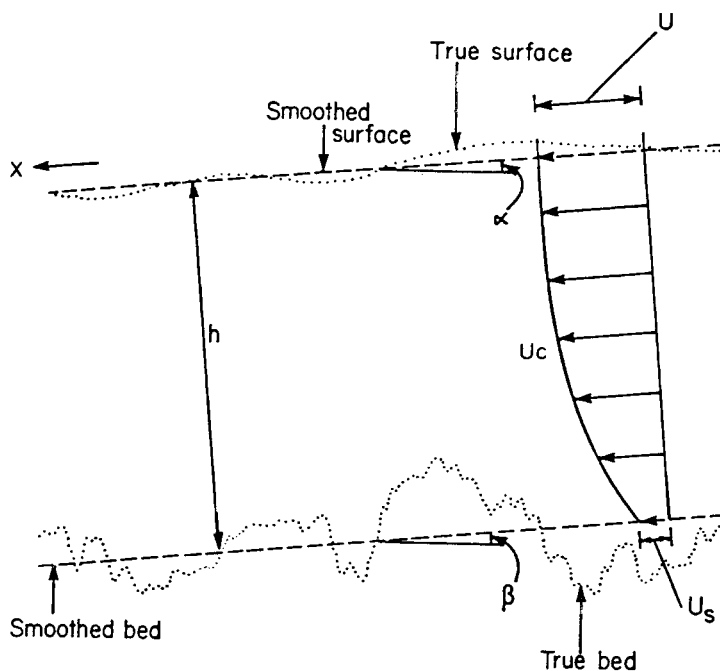


Figure 6. Idealised section through a glacier or ice-sheet, from Drewry (1986, fig. 1.6). Actual ice and bed surfaces are shown dotted whilst the parallel slab approximation is shown dashed (with slopes α and β). A velocity profile is illustrated defining total surface velocity (U), creep (U_c) and basal sliding (U_s). Ice thickness is given by h . (Copyright: Edward Arnold, London.)

the transport of the bluestone erratics over the topographic obstacles posed by the Preseli to Wiltshire route assuming the ice surface was close to the elevation of the source outcrops.

The upper limit on the size of a supraglacial boulder capable of being transported by a glacier is imposed by the size (areal extent, thickness) and velocity of the glacier in relation to the mass of the boulder. The addition of a large superincumbent mass to the ice load will increase normal stress which will increase shear stress (τ_p) and thus internal deformation (ϵ_s). Whilst it is possible theoretically to define critical threshold mass for a given glacier, such situations in nature are not common because it is unusual for individual blocks to approach the critical threshold mass as single coherent boulders without first fracturing into smaller particle sizes. This reduction in particle size occurs during gravity-driven mass movements, such as rock-falls, as potentially unstable rock masses exceed the limiting equilibrium on exposed bedrock faces and move to the glacier surface below. Most modern observations of mass movements from nunataks onto glacier surfaces consist of aggregations of individual particles well below the critical threshold mass.

Such supraglacially-derived material is often very coarse and angular (e.g. Lawson 1979; Boulton 1978), the absence of finer material resulting from meltwater removal and

lack of abrasion. Supraglacial diamicts are typically sandy, pebbly/bouldery muds of heterogeneous grain size often enriched in weak lithologies and far-travelled material (Eyles 1983). The enrichment in weak lithologies is consistent with Judd's (1902) view that the main bluestone types represent only the most resistant representatives of a formerly much more diverse but differentially weathered assemblage.

The transport distances of erratics are dependent on the mode of entrainment and routeway, supraglacial, englacial or subglacial, followed by the particle during ice movement. The interpretation that the Stonehenge bluestones were transported supraglacially has an important glaciological implication which relates to transport. If sediments are added to a glacier surface in the accumulation area they will be rapidly buried in the ice and englacial transport will ensue (Fig. 6); if added in the ablation area they will tend to remain at the surface (Drewry 1986). This implies that the Preseli district was already coincident with the ablation area of the glacier concerned and therefore located towards the margin of the ice mass. In this case the equilibrium line altitude (ELA) must have been greater than 350 m, the elevation of the Preseli Hills.

In terms of the mode of entrainment and transport, the mass of the Stonehenge erratics and the transport distance, the situation envisaged by Thorpe *et al.* (1991) is consistent with glacial geological observations and glaciological theory, but such a model would imply entrainment and deposition within the ablation area of the glacier concerned.

Surface microwear and particle shape

It has been noted that supraglacially-derived and transported particles are often very angular. This contrasts markedly with subglacial clasts which are characteristically sub-angular to sub-rounded as a result of clast-clast and clast-bed abrasion in the often debris-rich basal ice (e.g. Lawson 1979; Fig. 8); such subglacially transported clasts are also characteristically striated and faceted as a result of abrasion, and often as a result assume overall 'bullet' or 'blunt-nosed' shapes. It is obviously difficult to compare the majority of the Stonehenge bluestones with such clast characteristics because any surface dressing will have removed any original surface microwear features and changed the overall shapes of boulders. However, there is a body of evidence pertaining to such characteristics from a few apparently undressed Stonehenge bluestones which demands analysis.

Thorpe *et al.* (1991) note that the question of how many of the bluestones have been dressed remains controversial, but that many appear unworked and some, including nos 46 (rhyolite), 47 and 31 (both spotted dolerites) '... have rounded shapes consistent with natural boulders' (op. cit., 105-7). Despite the lack of apparent dressing none of these existing boulders has been reported to have any characteristically glacial features. However, Kellaway (1991b) does refer to striated erratics having been excavated at Stonehenge: '... a few have been striated and were therefore regarded by some archaeologists as being of glacial origin' (op. cit., 267). Kellaway notes that at the time of Colonel Hawley's excavation at Stonehenge in the 1920s a number of igneous and

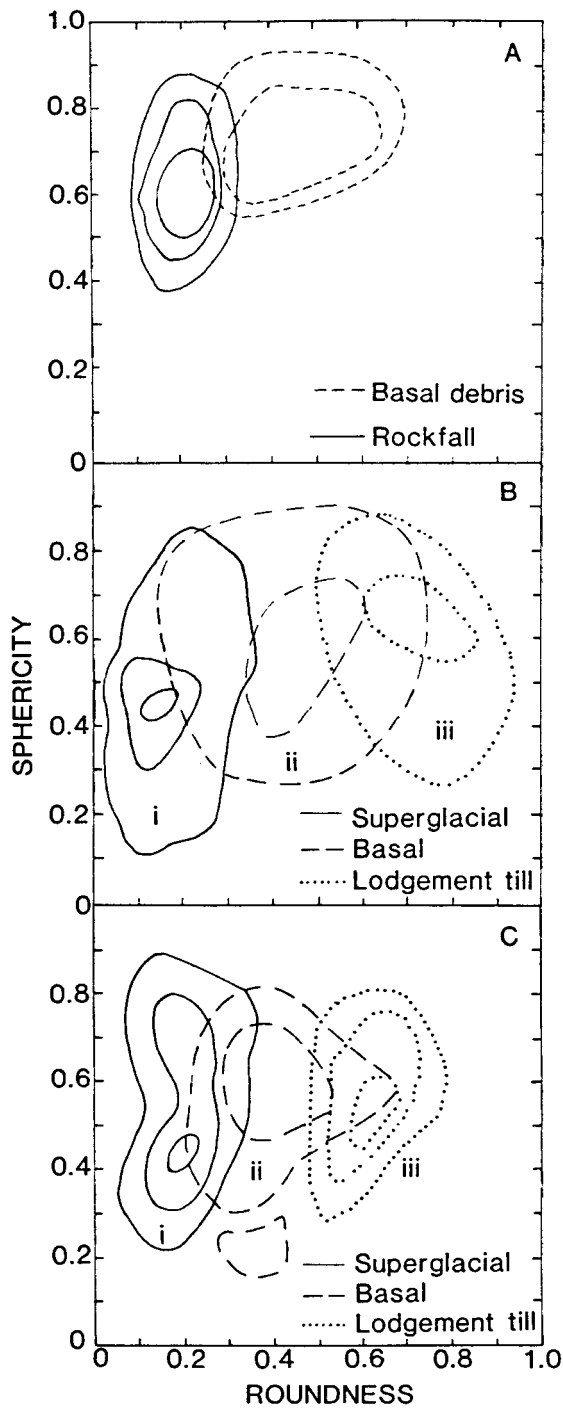


Figure 8. Roundness and sphericity of clasts (based on Krumbein's index) for material in transport in basal ice, supraglacial ice and in lodgement till, from Drewry (1986, fig. 7.13). (A) Samples from Breidamerjökull, Iceland (Boulton 1978). (B) Søre Buchanisen, Svalbard (Boulton 1978). (C) Grinnel Ice Cap, Baffin Island, Canada (Dowdeswell *et al.* 1985). Contours are at 5, 10 and 15% of data per 1% area. (Copyright: Edward Arnold, London.)

metamorphic rocks of Welsh origin were discovered: 'A few of these carried striations which appeared to be of glacial origin' (op. cit., 267). He draws attention to the discussion comments by Dale and Engleheart after Hawley's 1921 excavation report: '... one piece was striated, and he [Engleheart] thought they were all of glacial origin' (Engleheart 1921, 40). Thorpe *et al.* (1991) quote a letter written by Kellaway to the authors: 'In 1969–71 I came into contact with Mr R S Newall ... who told me that during Col. Hawley's excavations in the early twenties he drew attention to the appearance of rocks resembling glacial erratics. Hawley would have none of it, but Newall preserved some of this material for nearly half a century, before passing it to me for consideration' (op. cit., 107–8). Kellaway (1991b) figures this boulder, which is an Ordovician ignimbrite, similar to those from Snowdonia; it is clear from the photographs that this is a sub-angular to sub-rounded, faceted and bleached clast. What is less clear from the photographs are the claims that the boulder is striated, and that one side has been partially worked. Kellaway not only uses the evidence of this single boulder to support the glacial hypothesis, but also implicitly emphasises its North Wales source to argue for ice transport from a more northerly direction. Though Thorpe *et al.* (1991) were clearly aware of the existence of this boulder, they were unable to trace it, and they make no mention of Kellaway's reference to striae.

Given the nature of the derivation of this ignimbrite boulder, with the implication of suppression in Kellaway's letter, the integrity of the evidence deriving from it should be discounted unless and until reliable evidence is forthcoming as to its original context at Stonehenge. If, for the sake of argument, the evidence from this particular boulder, and the other largely circumstantial evidence for other striated boulders at Stonehenge (Engleheart 1921), is accepted as reliable, then a number of implications follow.

The presence of striations associated with faceted surfaces implies subglacial transport in a warm-based glacier. The potential for erratic transport in this situation is quite different from the supraglacial situation envisaged by Thorpe *et al.* (1991) and discussed above. If particles are either entrained subglacially by quarrying (Laitakari 1989), or derived supraglacially in the accumulation area and then descend to the subglacial zone (Fig. 7), then erratic survival and transport distances are a function of ice velocity and time in relation to crushing and fracturing of particles during ice flow (Donner 1989).

There is now a huge literature on erratic transport and dispersal generated as a result of studies related to ore prospecting, particularly in the shield areas of Canada and the Baltic (Shilts 1976; Eyles 1983). The detailed study of erratic trains and fans has been an essential requirement for ore prospecting in these areas as the distribution of ore-bearing erratics has been demonstrated to be an effective means of identifying valuable source rocks. The database on erratic transport paths is therefore extremely good and is of direct relevance to the Stonehenge bluestone problem. Donner (1989) has compared transport distances of Weichselian (Table 1) subglacially-entrained erratics in central Finland with those on the margins of the Baltic shield. In central Finland transport

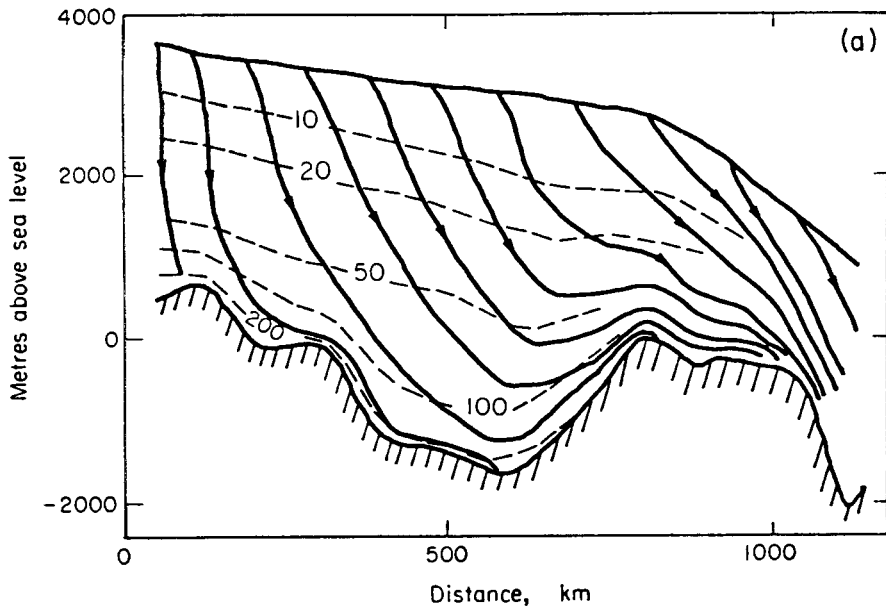


Figure 7. Computed steady-state particle paths (solid) and lines of constant age (broken) in units of 1000 years along a flow line in the Antarctic ice sheet from Vostok to near Wilkes, from Paterson (1981, fig. 10.6a) adapted from Budd *et al.* (1971). (Copyright: Pergamon Press, Oxford.)

distances from source are very short (usually <10 km). Pertunnen (1977) has noted that indicator erratics increase exponentially in the direction of ice movement as the ice flows over the source outcrop, and then decrease exponentially away from the distal contacts. 'Half-distance values', the distances at which the frequencies of the rock types are halved from the frequencies at the starting point of transport, range typically between 3 km and 6 km (Donner 1989). The 500 identified boulder fans in Finland have average half-distance values of only 1–5 km (Salonen 1987; Fig. 9).

However, on the margins of the Baltic shield transport of over 500 km has been documented (Fig. 10), and in North America erratics from Hudson Bay must have travelled between 1000 and 2500 km (Prest and Nielsen 1987). Donner (1989) notes that many of the far-travelled erratics on the margin of the Baltic shield are very large. Over 1900 erratic boulders with diameters over 3 m are known in Estonia, the largest being the rapakivi block 'Kabelikivi' near Tallinn with a diameter of 56.5 m, reported to be the largest Pleistocene erratic in NW Europe (Viiding 1976). Donner (1989) attributes the contrast in transport distances between the interior and margins of the shield to differences in the flow rates between the interior and marginal parts of the ice sheet (calculated from figures in Paterson 1981, 162; Fig. 11). There was simply not enough time available during the Weichselian glaciation to transport erratics from central Finland to the outer parts of the ice sheet, for instance to Estonia. A similar conclusion has been

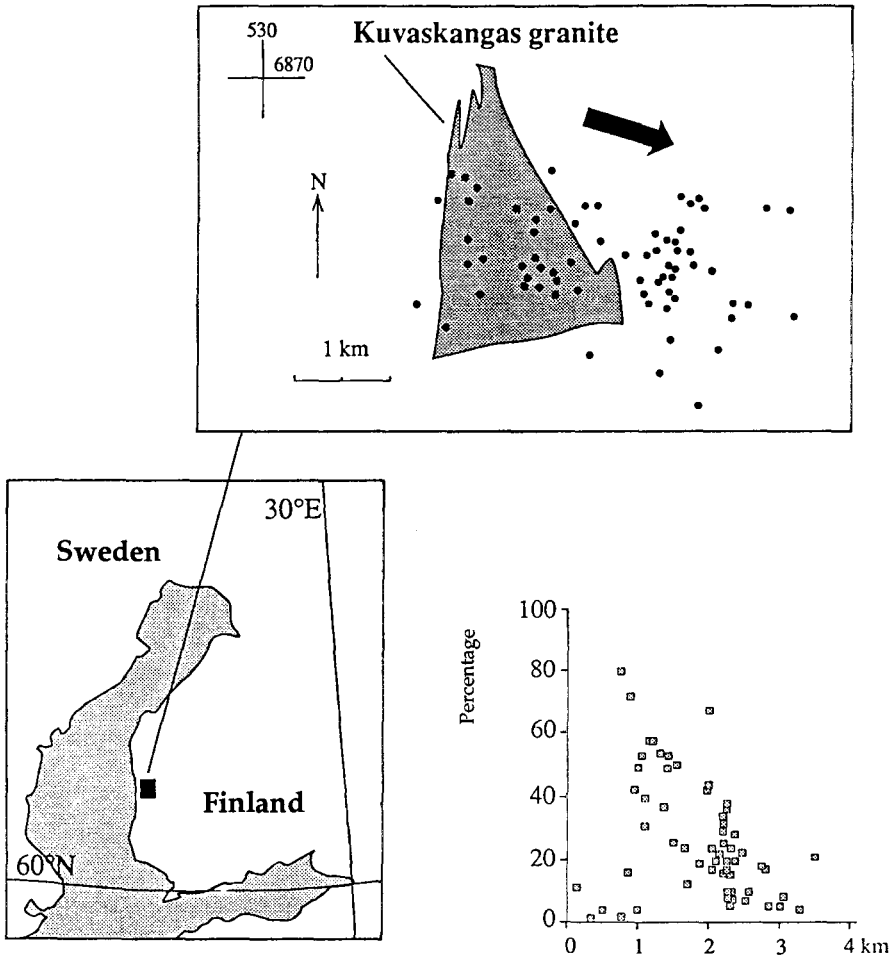


Figure 9. Location of the Kuvaskangas granite outcrop in Finland, from Salonen and Palmu (1989, adapted from figs 1 and 2). Boulder count sites shown as black dots. Graph shows percentage of boulders originating from the Kuvaskangas source in relation to the distance from the proximal contact of the rock. (Copyright: the Geological Survey of Finland.)

reached by Boulton *et al.* (1977) regarding the transport of erratics by the Late Devensian (Table 1) ice sheet covering the British Isles.

Therefore, though the transport trajectories of subglacially transported boulders are often very short as a result of crushing and fracture beneath the ice, there are substantial data to support the existence of large far-travelled striated clasts of subglacial origin in ice-marginal areas. Such an interpretation would imply that the Wiltshire Downs represent the terminal zone of the glacier concerned. There is therefore no inconsistency between the presence of subglacially transported boulders at Stonehenge and glacial geological observations and theory.

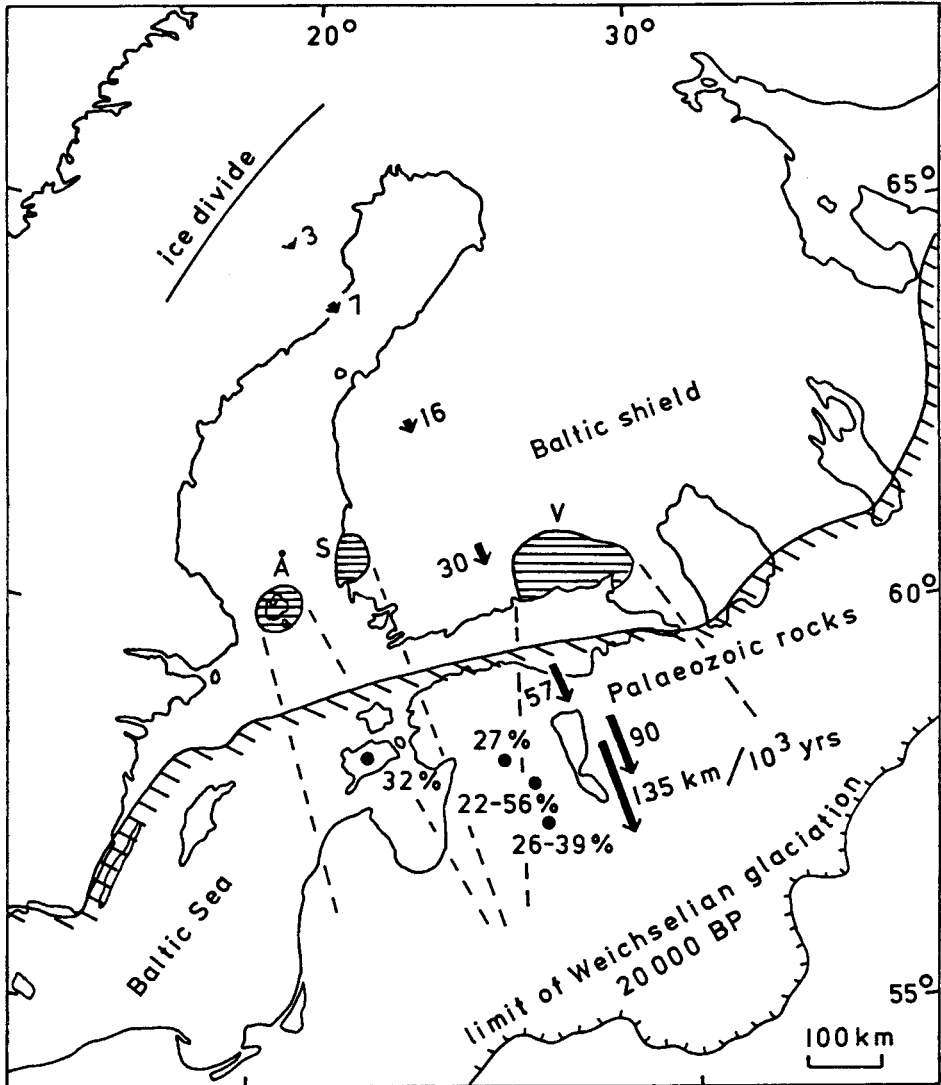


Figure 10. The proportion of erratics of crystalline rocks (in percentages) in parts of Estonia south of the boundary in the Gulf of Finland between the Baltic shield and the Palaeozoic sedimentary rocks, from Donner (1989, fig. 2). The outlines of indicator fans for the Åland rapakivi granite (Å), the Satakunta olivine diabase (S) and the Viipuri rapakivi granite (V) are shown, in addition to flow rates of the Weichselian ice sheet (after Paterson 1981) at various distances from the ice divide. The outer limit of the Weichselian ice sheet is also shown. (Copyright: the Geological Survey of Finland.)

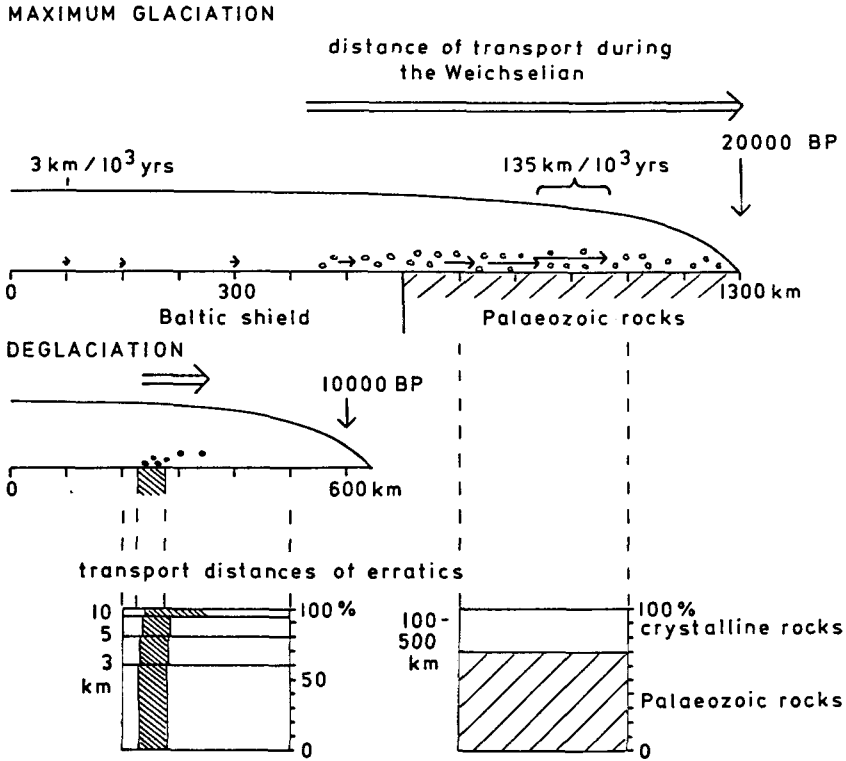


Figure 11. Profiles of the Weichselian ice sheet during its maximum at 20,000 BP and during deglaciation at 10,000 BP, from Donner (1989, fig. 3), showing typical transport distances of erratics of crystalline rocks from the Baltic shield in central Finland and the marginal area in Estonia. The flow rates used in Figure 10 are also shown. (Copyright: the Geological Survey of Finland.)

However, Kellaway (1991a) has suggested that the bluestones might have ‘... been carried for some distance downstream in floating ice’ (op. cit., 228) and thus implies that they were not deposited directly from glacier ice. Depending on the lithology, striations on glacial clasts are rapidly removed in meltwater streams as a result of particle corrosion and this would therefore conflict with Kellaway’s implication of extensive glaciofluvial outwash streams. On the other hand transport in river ice (Dionne 1972) can impart shallow striae to entrained clasts as they move across bedrock surfaces, so this mode of transport would not conflict with Kellaway’s claim that some of the Stonehenge bluestones are striated.

Pleistocene geology and geomorphology of southern Britain and adjacent shelves

ERRATIC DISPERSAL

In response to criticism of his earlier papers (e.g. Kellaway 1971), Kellaway (1991b)

has recently commented that '... the absence of a continuous chain of bluestone boulders heading all the way back from Stonehenge to the Preseli Mountains (thought by some to be the sole source of the bluestones) has been seriously urged as a valid reason for questioning their glacial origin!' (op. cit., 243). Despite Kellaway's apparent incredulity at such a suggestion, the examples cited above from Scandinavia and in North America provide convincing evidence that just such erratic 'trains' or 'fans' spreading from source to current location are typical of erratic dispersal by glacial transport. In recognition of this Thorpe *et al.* (1991) make considerable efforts to demonstrate continuity of the Preseli lithologies in a train from Pembrokeshire to Wiltshire. They review the evidence for presumed pre-Devensian transport of erratics from west to east in South Wales involving mainly Irish Sea sedimentary and igneous rocks, citing Bowen's (1970) compilation of Griffith's work (1937, 1939, 1940; Fig. 12) and additional recent evidence (Jenkins *et al.* 1985). They note from this that ice from the Irish Sea containing Pembrokeshire erratics did pass at least as far as Cardiff, with identical dolerites to the Stonehenge bluestones being transported as glacial erratics in south Dyfed (Strahan *et al.* 1914), and as isolated boulders as far as the island of Flatholm in the Bristol Channel.

This large dataset on erratic dispersal paths in South Wales is the result of decades of field research by many workers and is widely accepted as reliable. Whatever the age of the glaciation(s) concerned it is clear that the Irish Sea ice on crossing Pembrokeshire from north-west to south-east changed direction to west-east on entering the Bristol Channel area. The erratic transport paths clearly indicate movement of the Irish Sea ice in precisely the direction to be expected if it were to continue flowing towards Wiltshire; the consistency of the flow lines is striking.

In addition, the patterns of dispersal and concentrations of the Preseli dolerites as documented by Strahan *et al.* (1914) for Pembrokeshire itself (Fig. 13), and Thorpe *et al.* (1991) for the wider area, are entirely consistent with current theory on erratic dispersal (Figs 9 and 10; Donner 1989; Salonen and Palmu 1989). The spotted dolerite boulder train documented by Strahan *et al.* (1914) demonstrates the fan-shaped dispersal pattern with decreasing concentration away from source in a south-easterly direction, and the progressively isolated occurrence of spotted dolerite boulders further west in South Wales with increasing distance from source would be predicted by current theory (Pertunnen 1977; Salonen 1987). In fact, the distribution fits theory so well that it would be possible to locate the spotted dolerite source from the erratic dispersal path as in ore prospecting. This is what Thomas effectively did when mapping this area: 'The region immediately to the east and north of Narberth contained many examples [of boulders of spotted dolerite], and when an envelope was drawn around the occurrences it was found that the axis of the envelope pointed directly to the Prescelly Mountains' (Thomas 1923, 249; Fig. 13).

Despite this overall consistency between the erratic dispersal patterns in South Wales and the glacial hypothesis, the occurrence of a concentration of an assemblage of far-travelled boulders from Pembrokeshire in a small area of the Wiltshire Downs is not

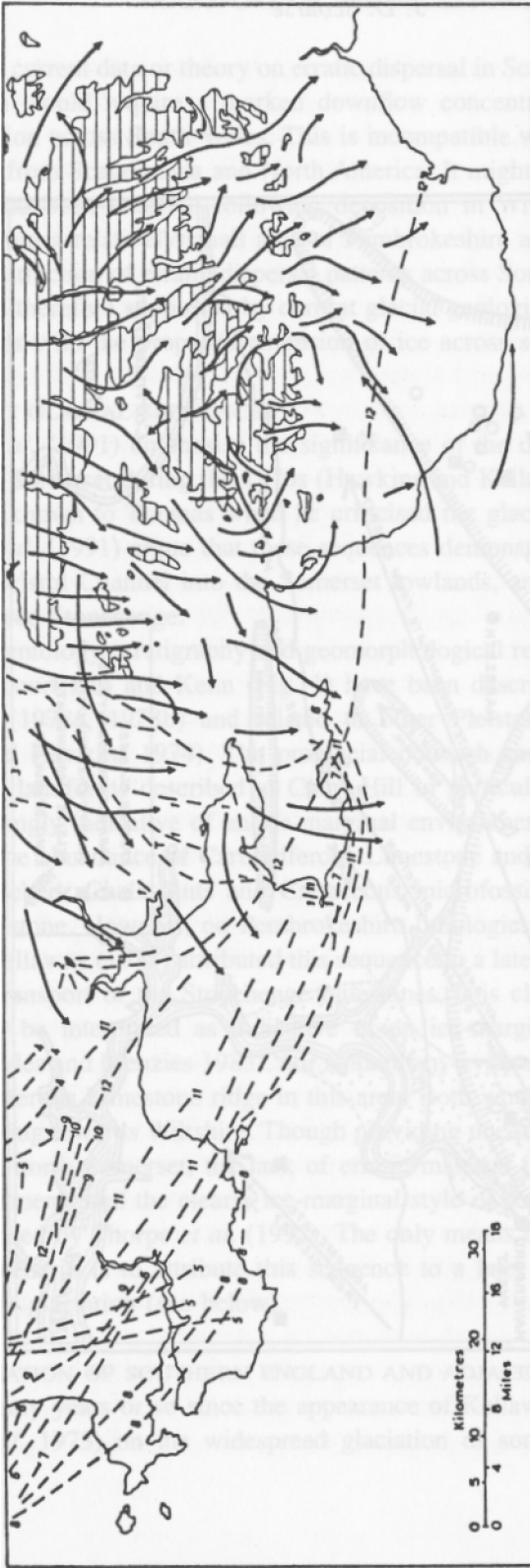


Figure 12. Ice movement in South Wales, from Bowen (1970, fig. 9.3) and Thorpe *et al.* (1991, fig. 15). Land over c.330 m shaded. Continuous lines based on striae and general erratics. Broken lines represent indicator fans after Griffiths (1940): (1) Llangynog rhyolite, agglomerate and diabase. (3) Builth Wells olivine dolerite. (4) Preseli 'diabase', rhyolite and 'spotted slate'. (5) Roch-Haycastle andesite. (6) St. David's granite. (7) Ramsey Island quartz albite porphyry. (8) St. David's Head gabbro. (9) Clegyr agglomerate. (10) Llandeloy porphyrite. (11) Harlech (Barmouth) grit. (12) New Inn pyroxenic keratophyre. (T) Trilobites (*Asaphus* or *Ogygia*) from the Ffairfach Grit near Llandeilo. (Copyright: Longmans, London.)

(Scale — 1 inch = 3 miles.)

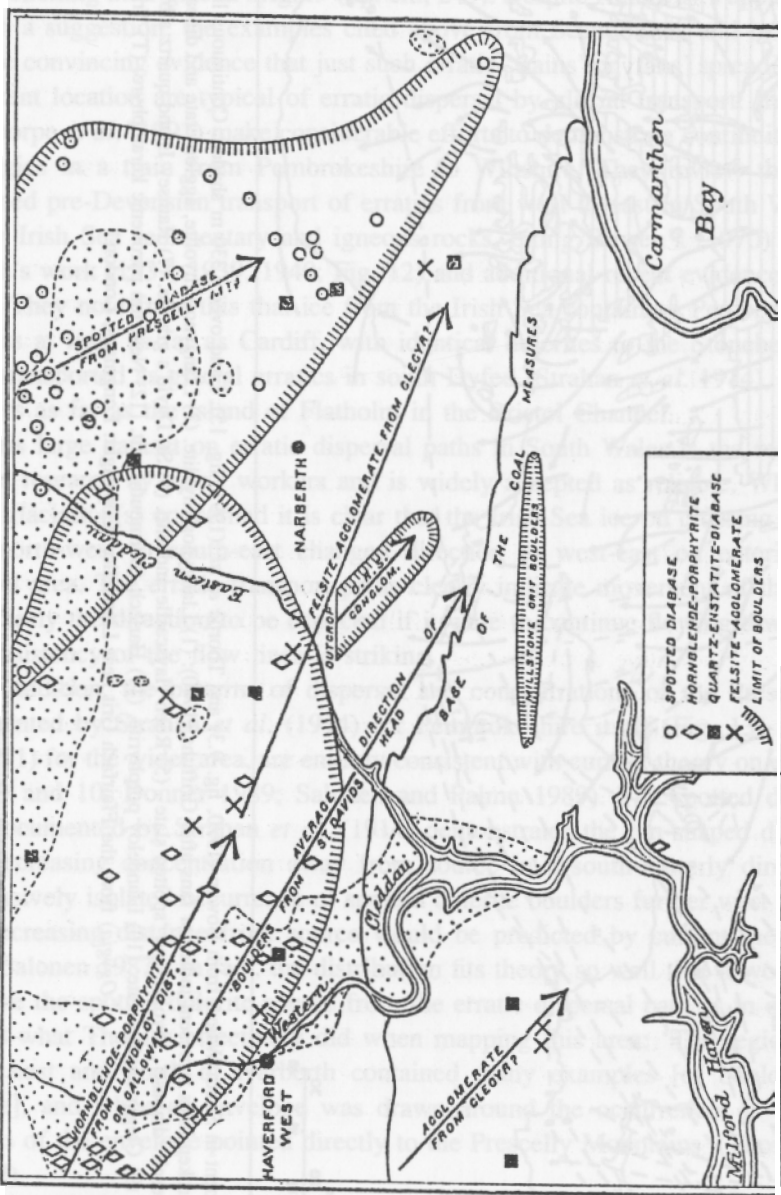


Figure 13. Map showing the distribution of glacially-transported erratic boulders in the Haverfordwest district, from Strahan *et al.* (1914, fig. 20). The spotted dolerite ('diabase') boulder train from the Preseli Hills is shown in the north-eastern part of the map. The north-west to south-east flow lines, and the downflow dilution of erratics from source, are clear.

consistent with current data or theory on erratic dispersal in Scandinavia or North America. Such a pattern would require a marked downflow concentration in the Wiltshire area following dilution across South Wales. This is incompatible with dispersal theory and the empirical data from Scandinavia and North America. It might be compatible if one single large erratic had been quarried following deposition in Wiltshire, but the diversity of erratic types from a relatively small area of Pembrokeshire at Stonehenge argues against this. The reconstruction of erratic dispersal patterns across South Wales erected by Thorpe *et al.* (1991) is therefore supported by current glacial geological theory and observations; however, it fails with the proposed extension of ice across southern England.

THE SOMERSET GLACIAL SEQUENCES

Thorpe *et al.* (1991) emphasise the significance of the discovery of glacial sediments in north Somerset during the 1970s (Hawkins and Kellaway 1971; Kellaway 1971). These were unknown to Thomas when he criticised the glacial hypothesis in the 1920s, and Thorpe *et al.* (1991) argue that these sequences demonstrate the ingress of Irish Sea ice from the Bristol Channel into the Somerset lowlands, and thus a little further along the route towards Stonehenge.

The sedimentology, stratigraphy and geomorphological relationships of the glacial sequences at Court Hill and Kenn (Fig. 1) have been described in detail by Gilbertson and Hawkins (1978a, 1978b) and related to other Pleistocene sequences in the area (Gilbertson and Hawkins 1974). The proglacial outwash and glaciolacustrine sediments and associated landforms described at Court Hill in particular (Gilbertson and Hawkins 1978a) are strongly indicative of an ice-marginal environment. Derivation from the west is clear from the abundance of Carboniferous Limestone and Rhaetic rocks, the presence of Greensand chert, Chalk-flints and Cretaceous microfossils and the absence of Coal Measures sandstone. However, no Pembrokeshire lithologies have been reported.

Though Kellaway (1971) attributed this sequence to a later glaciation than that responsible for the transport of the Stonehenge bluestones, it is clear that the data from these sites can only be 'interpreted as indicative of an ice-margin. This is not a subglacial landsystem (Eyles and Menzies 1983), nor is there any evidence of major glacio-tectonism of the Carboniferous Limestone ridge in this area. Both would be expected if the ice had continued flowing towards Wiltshire. Though providing unequivocal evidence for the presence of ice in north Somerset, the lack of erratic material from Pembrokeshire in these glacial sediments and the clearly ice-marginal style of sedimentation conflict with the scenario proposed by Thorpe *et al.* (1991). The only means of accommodating these data within their scenario is to attribute this sequence to a later glacial episode unrelated to the Stonehenge glaciation (see below).

WIDER GLACIATION OF SOUTHERN ENGLAND AND ADJACENT SHELVES

In the twenty years or so since the appearance of Kellaway's views (Kellaway 1971; Kellaway *et al.* 1975) on the widespread glaciation of southern England and adjacent

shelves, not a single piece of convincing evidence has been forthcoming to support this conviction. This is despite intensive mapping of the offshore region (Fannin 1989) and detailed site investigations of very many important Pleistocene localities across southern England. The original criticisms made by Green (1973) and Kidson and Bowen (1976) during the 1970s remain valid. To these may be added a whole series of others. The Burtle Beds have been shown to be marine, estuarine and freshwater beds (Kidson *et al.* 1978) of composite interglacial age (probably oxygen isotope stages 5e and 7; Bowen and Sykes 1988; Campbell *et al.* in press). There is no evidence for glaciation in the Somerset lowlands other than at Court Hill and Kenn (cf. Hunt *et al.* 1984). The erratics on the shore platform around Devon, Cornwall and along the Channel coast of both England and France are unlikely to have been emplaced by grounded ice and are much more convincingly explained both stratigraphically and sedimentologically as sea-ice or iceberg rafted (Van Vliet-Lanoë 1988; Hallégouët and Van Vliet-Lanoë 1989; Bowen 1994; Scourse 1996). Apart from the glacial sequence at Fremington (Croot *et al.* 1996), there is no evidence for any pre-Devensian glaciation of the Celtic Sea or of the English Channel. Glacigenic sediments do occur on the Isles of Scilly (Fig. 1) and in the Celtic Sea but these are localised in extent and relate to a Late Devensian surge of thin ice over deformable substrate beyond the stable margin of the ice in the St. George's Channel area (Scourse *et al.* 1990; Scourse 1991). This ice did not flow eastwards, but was instead topographically constrained south-westwards and had a glacial marine terminus. There is no evidence that Cornwall was ever glaciated (Scourse 1985a, 1985b, 1996). The current view is that the Fremington Till of north Devon (Fig. 1) is probably of glacigenic origin and may be Anglian in age; it is rich in derived Tertiary microfossils from the offshore Stanley Banks Basin immediately to the north (Croot *et al.* 1996; Fig. 5), but is very limited in extent.

The Axe Valley gravels in east Devon have been shown to be of periglacial fluvial origin (Green 1974, 1988; Shakesby and Stephens 1984), as have the gravels of the Hampshire Basin (Green 1973; Gibbard and Allen 1994; Fig. 1). The morainic evidence at Selsey is non-existent. The Slindon Sands (Fig. 1) are unequivocally of littoral interglacial origin; since the 1980s very detailed archaeological excavations in these and associated sediments have demonstrated the earliest hominid site in Britain with abundant associated artifact, macro- and microfossil evidence (Roberts 1986; Roberts *et al.* 1994). No evidence to support glaciation has been forthcoming. The palaeovalley system of the Channel relates to low-stand extension of periglacial fluvial networks during cold-stage lowstands (Hamblin *et al.* 1992; Bellamy 1995) and in part possibly to overflow of an ice-dammed lake in the southern North Sea through the Strait of Dover during the Anglian (Smith 1985, 1989; Gibbard 1988, 1995). The submerged clifflines are probably of littoral lowstand origin (Scourse *et al.* 1990). The concept of a large ice mass on the continental shelf west of the British Isles is not supported by any stratigraphic or geomorphological evidence, either on the shelf or down the continental slope; neither is there any observational or modelling evidence for major glacio-isostatic rebound in this area which would accompany deglaciation of such a large ice mass.

The only possible and indirect support for the notion of the glaciation of the English Channel has been provided by Wingfield (1989) who suggested this on the basis of the occurrence of deep enclosed incisions attributed to jökulhlaup discharges. This view has, however, itself been heavily criticised (Hamblin 1990; Jeffery 1990).

In the light of this bank of evidence must be laid the charge that Kellaway (1971; Kellaway *et al.* 1975) did not sufficiently consider alternative hypotheses to explain features or sediments which he attributed to glaciation. That this is so is clear enough in the instances given above, but there are other examples. In interpreting the Slindon Sands as glaciofluvial Kellaway *et al.* (1975) emphasised the limited lateral extent of these deposits: '... one is struck by the severely limited extent of these deposits to coastal Hampshire and Sussex. No other fully authenticated marine deposits at this level are known from the shores and islands of the English Channel. This contrasts sharply with the widespread occurrence of raised beaches at a level 5–8m above present sea level in the same area, that are attributed to the high sea level of the Eemian interglacial. We consider it very curious that the supposed major interglacial stand of sea level at the Slindon level should have left such limited extent of its presence' (*op. cit.*, 199). This was an astute observation but the wrong conclusions were drawn; this area has been tectonically uplifted since the Middle Pleistocene, unlike the areas to the west and east (Preece *et al.* 1990), so the limited spatial outcrop can be explained by regional uplift and has nothing to do with glaciofluvial sedimentation. The 'meltwater' channels in the Bristol district may indeed be partly of glacial origin, but many of the others can be explained alternatively in terms of drainage superposition, high-magnitude low-frequency flood events (*cf.* Hanwell and Newson 1970), periglacial fluvial channels or even exhumed Permo-Triassic wadi channels. These hypotheses require testing. The oversteepening and subsequent cambering of slopes in the Bath district can be more convincingly attributed to a combination of periglacial and fluvial processes than to glaciation (Hutchinson 1991; Parks 1991; Ballantyne and Harris 1994).

The only unequivocal evidence for the Pleistocene glaciation of southern England and adjacent shelves occurs in very localised areas of north Somerset, north Devon, the Isles of Scilly and more extensively in the Celtic Sea. The shore erratics are probably related to glacimarine rather than glacial processes. The remainder of southern England and adjacent shelves remained unglaciated during the Pleistocene. The scenario envisaged by Thorpe *et al.* (1991) is thus seriously weakened by their reliance on an hypothesis for which there is no supporting evidence.

THE NORTHERN AND MORETON DRIFTS AND THE SOLENT RIVER

Kellaway (1971) interpreted the Northern Drift (or 'Plateau Gravel') of the Cotswolds and north Oxfordshire (Fig. 1) as glacial in origin, and used this interpretation as supporting evidence for widespread glaciation during the 'Anglian' of central southern England. In his recent papers, Kellaway (1991a, 1991b) also interprets the Northern Drift as glacial in origin, and this forms a plank in his argument for the emplacement of the

Stonehenge erratics by ice and ice-related processes with glaciation from a northerly direction.

The Northern Drift Formation (Hey 1986) consists of scattered outcrops or patches of unstratified reddish sandy clay containing pebbles of Midlands (notably Bunter quartzite) origin. The Formation occurs both at high elevations on the Cotswolds and at lower elevations within the river valleys draining the Cotswold dip-slope, notably the Evenlode. In a recent re-examination of the Northern Drift Formation, Hey supports the conclusion of Shotton *et al.* (1980) that the lower elevation deposits are, for the most part, Anglian and pre-Anglian decalcified river gravels deposited by a river flowing down the present Evenlode Valley and tributary with the Thames system, and not glacial as suggested by Kellaway (1971; Kellaway *et al.* 1971) and earlier workers (Geikie 1877; Pocock 1908; Sandford 1926; Tomlinson 1929; Dines 1946; Arkell 1947a, 1947b). However, Hey also concurs with Shotton *et al.* (1980) in suggesting that the scattered pebbles on the Jurassic uplands might be of glacial origin '... these being the remnants of a till laid down by an ice-sheet advancing from the Midlands' (Hey 1986, 291). This conclusion has been supported by Worssam (1987) on the basis of stone-count data from a high-level exposure on the dip-slope of the Cotswolds. Worssam favours a glacial origin because the pebbles include ironstone from the Lias which outcrops at lower elevations. On the other hand, scattered pebble exposures on the southern Cotswolds are rich in flint, and glaciers introducing these from the south or east seem unlikely; these high-level exposures might therefore be explained alternatively as decalcified fluvial gravels of Tertiary age (R.W. Hey, pers. comm. 1996).

The glacial sequence of the Vale of Moreton (Fig. 1) has been described in detail (Bishop 1958) and is the nearest exposure to the north of Stonehenge of unequivocal glacial sediments. This supraglacial sequence contains proglacial outwash sediments and glaciolacustrine beds which clearly indicate ice-marginal conditions. As in the case of the Court Hill glacial sequence, there is no evidence here for dynamic subglacial sequences, landforms or tectonism which would be expected if this area had been overridden by a glacier flowing onwards towards the south. The Moreton Drift therefore represents an ice-marginal sequence, and there is some limited support for the interpretation of the high-level exposures of the Northern Drift Formation as glacial in origin which might support Kellaway's views (1971, 1991a, 1991b). However, the Midlands-derived pebble assemblages contained in both the Northern and Moreton drifts are entirely inconsistent with the Stonehenge bluestone assemblage and this weakens the significance of either the Northern or Moreton drifts to the Stonehenge problem.

Kellaway's recent (1991a, 1991b) scenario invokes river ice transport of the Stonehenge bluestones in the 'Southampton River' (= Solent river) fluvial or glaciofluvial gravels of which he identifies at Bathampton and Kingsdown (previously interpreted as glacial; Hawkins and Kellaway 1971; Fig. 5). This derives from an earlier idea of Varney (1921) who suggested that the Bathampton gravels might provide a link between the Avon and earlier headwaters in Wales. The continuous and thick fluvial gravels of

the Solent river across east Dorset and Hampshire have recently been examined in detail by Gibbard and Allen (1994). This work supports the conclusion of Green (1973) that nowhere in this sequence is there evidence at any time for glacial input within the catchment (P.L. Gibbard, pers. comm. 1996). Not only is there is no geological evidence which supports Kellaway's view that the Solent river was an important conduit for the transport of the Stonehenge bluestones, but there is only very superficial evidence that the catchment of the Solent ever extended into the Bath-Wiltshire area, let alone Wales as he suggests.

GEOMORPHOLOGY OF THE CHALK ESCARPMENT

If the Wiltshire Downs had been glaciated by ice flowing from either the west (Kellaway 1971; Thorpe *et al.* 1991) or north (Kellaway 1991a, 1991b), the Chalk escarpment would at some point have been overridden by ice. Boulton *et al.* (1977) noted the striking change in the escarpment at the point where this crosses the accepted limit of Pleistocene glaciation in Hertfordshire. To the south, in the unglaciated area, the scarp has an altitude of some 250 m. To the north it is irregular and much lower, descending to only 90 m in northern East Anglia. They suggest that the scarp crest has been lowered by glacial erosion in excess of 100 m and set back by around 3 km. Bromley (1967) has also noted the southward and upward glacio-tectonic thrusting of huge masses of Chalk within the glaciated section of the scarp. Such geomorphological and glacio-tectonic structures are absent in the sections of the Chalk scarp expected to have been overridden if the Wiltshire Downs had been glaciated.

Ice-flow directions and glaciology

Thorpe *et al.* (1991) review evidence on the entrainment, transport and deposition of boulders by glaciers and claim this as support for the glacial hypothesis: 'In many areas erratic boulders are irregularly distributed on the surface of older till or bedrock, with no apparent matrix. These are termed "free boulders" (Flint, 1957, 129–130) and may reflect derivation from nunataks, removal of matrix by erosion, association with deflation, or deposition from clean glacier ice in a free condition' (op. cit., 148). In support of this latter concept they again cite Flint (1955) who interpreted the contrast between normal till ('boulder clay') to the east of the Missouri with bouldery till to the west, and attributed this to the Missouri river trench acting as a 'baffle' or 'cleat'. In this case '... the upper part of the ice unimpeded by the baffle flowed easily westward. The upper part of the ice mass, however, contains very little drift, and that little more is likely to be of distant origin' (op. cit., 148). The clear implication is that the limestone uplands of the Mendips, north Somerset and the chalk scarp of the Wiltshire Downs acted as such a baffle to strip supraglacial ice containing the large far-travelled unstriated erratics from Pembrokeshire from the basal ice rich in debris of more local origin. Such a concept of englacial shear caused by topographic highs, in which upper clean ice moves rapidly

forwards over stationary or slow-moving debris-rich ice beneath, is very problematic indeed.

The Glen Flow Law (1) and the driving stress equation (2) indicate that the greatest flow deformation occurs in the basal ice, where the ice column is thickest, with a progressive reduction in deformation upwards through the glacier. Glaciers therefore flow by sliding over the bed or deforming predominantly in the basal region. Significant englacial shear of the kind required by Thorpe *et al.* (1991) is therefore difficult to reconcile with glacier physics.

However, there are both observational and modelling data to support the notion of limited englacial shear in particular situations. Drewry (1986) demonstrates how shearing can take place as a result of longitudinal compressive stress at specific temperature and bed roughness boundary conditions. The englacial shearing or thrusting can cause small steps in the glacier surface (Paterson 1981). In a tunnel in the icefall on Blue Glacier, Kamb and LaChappelle (1968) observed that the foliation near the bed was offset by many shallow thrust faults in a direction compatible with the direction of shear in the overall flow. In situations where glaciers move from a warm-based to a cold-based condition asymmetric folding can develop in the basal ice which may eventually develop into overturning or thrusting (Boulton 1972). Such shear thrusting is most common in glaciers in which the accumulation zone is warm-based and the ablation zone cold-based; in such cases the frozen subglacial layer represents an extension of the permafrost. Such polythermal glaciers are common in Svalbard (Schytt 1969; Boulton 1972) but similar situations have been observed in Antarctica (Drewry 1986). Where subglacial materials are frozen to the basal ice the adhesive strength between the glacier sole and the bed is greater than the shear stress across the contact so no basal sliding occurs, and failure instead takes place just above the bed within the ice (Boulton 1972).

Boulton (*op. cit.*, 9) notes that where frozen bed is relatively thin then '... there exists the possibility of quarrying or plucking of very large erratics by the glacier'. In this case failure takes place not within the ice but within the bed. This situation is described in Figure 14. If the frozen mass is assumed to be rigid, the critical force is the shear stress at the bed. Fracture will occur if:

$$\tau l \geq F \cdot AB + (N - u) \tan \phi BC \quad (3)$$

where τ is shear stress along the line ABC, F is the shear strength of the frozen sediments and $(N - u) \tan \phi BC$ is the frictional resistance along BC, N being the average normal load across BC in the absence of cohesion. Fracture is more likely if l/AB is large because values of F are likely to be greater than τ . High pore-water pressure will reduce the strength of the sediments by reducing F . Boulton suggests that this mechanism could explain the plucking of large erratics such as the Chalk clasts embedded in the Anglian tills of the Norfolk coast. The mechanism is relevant to the Stonehenge problem because it provides a means of entraining large erratics in association with englacial shearing.

However, there are a number of attributes of this process inconsistent with the

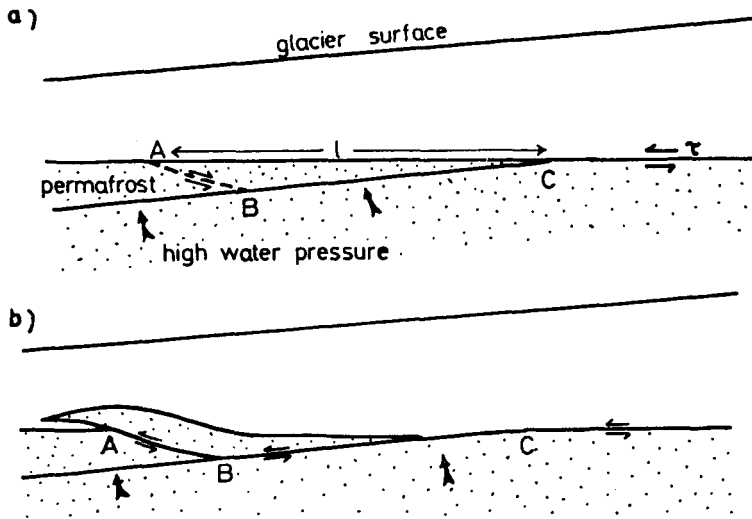


Figure 14. Schematic representation of the mechanism responsible for the plucking of large erratics where the glacier is cold-based but where the subglacial permafrost is thin (from Boulton 1972, fig. 4). (Copyright: the Institute of British Geographers.)

Stonehenge case. First, any failure within the ice will occur close to the bed because this is where τ is greatest; it will not occur high in the englacial zone. Second, the entrainment of large erratics can only occur in cold-based situations, and in particular where the ice moves onto permafrost. In the Stonehenge case this would be represented by the point where the ice moves over the 'baffle' or 'cleat' of the north Somerset and Wiltshire. The resultant sediments should therefore contain not erratics from Pembrokeshire but large clasts of the Carboniferous and Jurassic limestones and Chalk characteristic of this area. Third, Boulton (1970, 1972) notes that thrusting results in the movement of basal sediments upwards along shear planes, and in the movement of englacial material to a higher level. Deposition from such thermally complex glaciers is therefore characterised by ablation and flow tills associated with large quarried blocks and an absence of lodgement till; such an assemblage is absent from the Wiltshire Downs (see below). Finally, all the observed examples of such glacial or within-bed shear are at orders of magnitude smaller than the extent of shear required in the Stonehenge case.

Similar englacial shear propagated by frozen topographic highs has been invoked by Shaw (1979) to explain englacial fold complexes called 'Rogen moraines' which are common in glaciated shield areas. Such moraines form in areas of moderate bedrock relief with frozen zones on bed highs in situations where the local topography favours ice spreading and divergent flow. However, these features are characterised by the stacking of thick englacial debris sequences which are completely absent in the Stonehenge case (see below), and the topographic differentials required are much smaller than the 'baffle' posed by the Somerset-Wiltshire uplands.

These cases therefore provide no support for the 'baffle' concept suggested by Flint (1955) and adopted by Thorpe *et al.* (1991). In the absence of substrate thermal contrasts the observational and theoretical data indicate that englacial shear does not occur upflow of large bedrock highs and that ice slides and basally deforms around and over such obstacles (Fig. 7). Alternatively a downglacier transition from warm- to cold-based ice results in a sediment assemblage inconsistent with the regional geology.

There is another important sense in which the scenario envisaged by Thorpe *et al.* (1991) is implausible from a purely glaciological point of view. Drawing on the earlier views of Kellaway (1971) and Kellaway *et al.* (1975) they state that the Irish Sea glacier on exiting from the Irish Sea into the Bristol Channel was topographically constrained by Exmoor to the south and the South Wales Coalfield to the north before moving uphill towards Salisbury Plain. It has been noted that the driving stress equation (2) explains how glaciers are able to flow over topographic obstacles. If ice flow is topographically constrained, as Thorpe *et al.* (1991) have suggested, then this implies that the direction of the surface slope (α_s) was consistent with the bed topography. This in turn implies that the ice thickness (h) was relatively small. This explains why glaciers tend to be more influenced by topography towards their margins as ice thickness decreases towards the terminal zone. It is clear that the Irish Sea ice stream during the Late Devensian (Scourse *et al.* 1990; Scourse 1991) behaved in just such a way, and the divergent fanning-out of pre-Devensian Irish Sea ice into the Celtic Sea and Bristol Channel area is clear from the erratic train evidence from South Wales (Bowen 1970; Fig. 12). From this it follows that if the ice surface gradient was consistent with the bed topography in the Bristol Channel it should remain consistent on exiting from the Bristol Channel. The proposal that the ice did not do this, but instead ascended the high ground of north Somerset, is not consistent with glacier physics. Ice flow discordant with bed topography can only be explained if the ice surface slope is similarly discordant. Therefore the only way in which the ice could have overcome this topographic obstacle is if the surface slope was orientated west-east from South Wales towards Wiltshire which would in turn imply relatively thick ice with an ice-dispersal centre on the western continental shelf, or in south-west England, or both. This requirement is also consistent with the earlier observation that the Preseli Hills were in the ablation area of the glacier. There is no evidence in either area for such a large ice mass.

Lack of glacial sedimentary sequences on the Wiltshire Downs

Perhaps the strongest argument against the glacial hypothesis is the lack of convincing glacial sedimentary sequences anywhere close to the Wiltshire Downs east of the Clevedon district of Somerset and south of the Vale of Moreton. This was raised as a serious problem by Thomas (1923) and remains as serious in the light of recent data. Recognising this problem, Thorpe *et al.* (1991) attempt to explain the occurrence of isolated erratics as the product of sedimentation from clean, supraglacial, ice. That such

ice should be sheared from debris-rich basal ice has been shown above to be glaciologically implausible. It is also implausible in the light of glacial geological evidence. All the erratic dispersal evidence from Scandinavia and North America discussed above concern erratic boulders contained in, or on the surface of, thick glacial drift sequences. In lowland Estonia at the margin of the Baltic shield, for instance, the drift forms an almost continuous cover between 5 and 10 m thick. The same is true of the erratics dispersed by the Cordilleran ice sheet in North America. The only situation in which 'free erratics' occur on bedrock isolated from glacial sediments, which is the scenario envisaged by Thorpe *et al.* (1991), is in the region of intense glacial erosion close to ice-dispersal centres such as the highlands of North Wales and Scotland (Fig. 15). Ice-marginal areas are typically characterised by complex landform-sediment assemblages associated with proglacial outwash and glaciolacustrine sequences (Eyles 1983). There are no such sequences anywhere near Stonehenge, even in *remanié* form.

Problems with the glacial hypothesis: a summary

Though it has been demonstrated that bluestone-sized erratics can be transported many hundreds of kilometres as large unstriated blocks in supraglacial ice or as striated boulders in sub- and englacial routeways, the precise requirements for the transport of the Stonehenge bluestones are not consistent with either observational or modelling data in glaciology or glacial geology. The major problems are:

1 The lack of glacialic sediment sequences and depositional landforms close to Stonehenge on Salisbury Plain, or between Stonehenge and either the Vale of Moreton or north Somerset. Erosion and removal of such sediments is falsified by the absence of glacially-derived materials in the gravels of rivers draining Salisbury Plain, and of any *remanié* glacial materials on the Wiltshire Downs other than at Stonehenge itself.

2 The lack of glacio-tectonic structures expected if the Chalk escarpment had been overridden by ice.

3 The inconsistency between the driving stress equation (2) and the topographic characteristics of the proposed route between Preseli and Stonehenge.

4 The inconsistency between the observational and theoretical data on englacial shear and associated sedimentary sequences, and the regional geological data.

Additional evidence post-1991

Clearance of erratic boulders from Salisbury Plain

Thorpe *et al.* (1991), in support of the glacial hypothesis, emphasise some observations by de Luc (1811) made in the late eighteenth century (Bartenstein and Fletcher 1987). It is claimed that between 1780 and 1805 de Luc noted the removal of large boulders during field clearance on Salisbury Plain, and that whilst some of this material was local, much

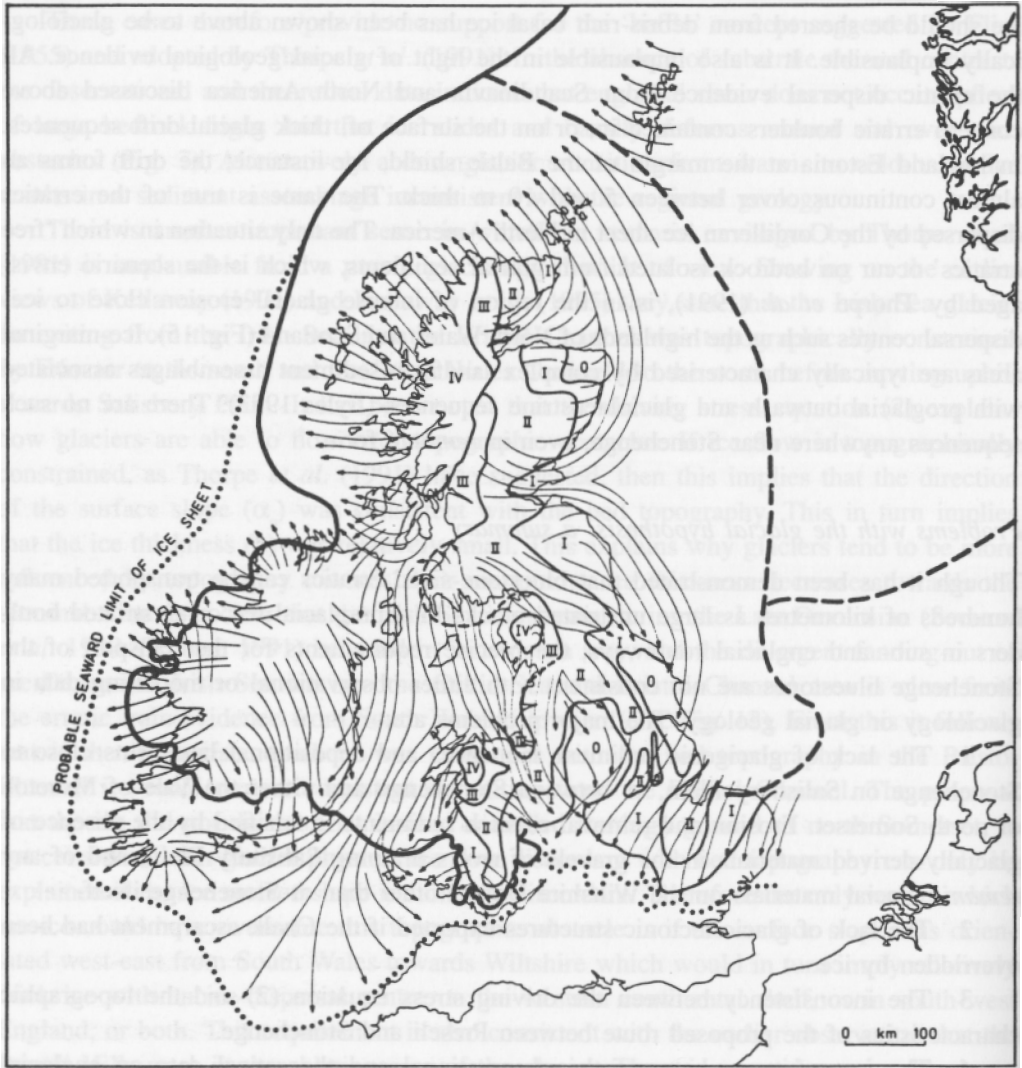


Figure 15. Pattern of ice-sheet movement over Britain and patterns of glacial erosion from Boulton *et al.* (1977, fig. 17.1). The dotted line shows the maximum extent of glaciation in Britain. The continuous line shows the assumed limit of the Late Devensian ice-sheet, dashed in the speculative North Sea area and omitted over central England. The arrows show generalised flow directions based on geological evidence. Zones of increasing erosional intensity, from 0 to IV are also shown. (Copyright by permission of Oxford University Press.)

of it was 'trap' (dolerite) and 'rhyolite' (granite). They therefore suggest this provides support for Judd's earlier contention that formerly '... Salisbury Plain was sprinkled over thickly with the great white masses of sarsen-stones ("greywethers") and much more sparingly with darker coloured boulders (the so-called "bluestones"), the last relics of the

glacial drift, which had been nearly denuded away' (Judd 1902, 118), a view also shared by Briggs (1976a, 1976b, 1977).

Darrah (1993) has pointed out, however, that the nature of de Luc's observations have been misinterpreted. In fact de Luc was contrasting Salisbury Plain with other counties further north where he had observed boulder fields in that it was conspicuously devoid of far-travelled material. De Luc '... is certainly not saying there were boulders of igneous rock in Wiltshire; indeed the contrary could be inferred' (Darrah 1993, 78).

Chlorine-36 date

Bowen (1994) reports a chlorine-36 date of 14,000 years BP from a Stonehenge bluestone and claims this as support against the glacial hypothesis. As this dating method provides an age for first exposure of a fresh rock surface, this result has therefore been interpreted to demonstrate that the bluestone concerned was '... still buried at its source outcrop during the Anglian (400ka), and did not become exposed by denudation to the atmosphere until the Late Devensian ... after which it was presumably quarried by prehistoric people and taken to Stonehenge' (Bowen 1994, 211).

In order for this date to provide conclusive evidence on this important matter a number of points require clarification. First, technical details are required to enable independent assessment of the dating procedure, or of potential errors in the method, along with standard deviations or error bars. Second, the exact provenance of the sample needs to be established. It is reported that the measurement was undertaken on '... an igneous rock from the Stonehenge collection in Salisbury Museum' (op. cit., 211). Further detailed description of the petrology of the rock to demonstrate the reliability of the date is required. Third, details need to be provided of the presence or absence on the rock surface of either anthropogenic dressing or natural microwear. These data are prerequisites for interpretation of this method which is reliant on surface exposure.

The interpretation of this date involves an *a priori* assumption that the glaciation concerned is the Anglian (Bowen 1994). Even if the date is accepted as reliable, it would not be inconsistent with glacial derivation during the Late Devensian. The interpretation also involves an *a priori* assumption that the bluestone was quarried by man. Equally the boulder could have been collected for use from a Late Devensian glacial source; exposure could therefore have been natural rather than anthropogenic. Consequently further clarification of technical details is required if this promising dating technique is to have a conclusive bearing on the bluestone controversy.

Age of glaciation

In the literature various ages are suggested for the glaciation responsible for the transport of the Stonehenge bluestones. An 'Anglian' age is preferred by Kellaway (1971),

Kellaway *et al.* (1975) and Thorpe *et al.* (1991), whilst Kellaway (1991a, 1991b) has recently suggested Pliocene glaciation at 2.47Ma. He derives this latter date from the presence of ice-rafted detritus in ODP552A in the Rockall Trough (Shackleton *et al.* 1984) and concludes that 'if, as seems likely, this ice developed primarily over Brittany, Ireland, Iceland and the western uplands of England, Wales and Scotland, then this would be the most likely time for movement of glacial erratics from Wales to Salisbury Plain to have taken place' (Kellaway 1991a, 215).

Aside from the fact that as there is no evidence for glaciation of Salisbury Plain at any time such age ascriptions are meaningless, this inference that the British Isles were glaciated in the Pliocene must be regarded as entirely speculative. To correlate deposits in the absence of any stratigraphical data whatsoever is to invite homotaxial errors of the most serious kind. It is most unsatisfactory that such correlations should appear in the literature because publication itself confers a reliability which is wholly unjustified. At least one other paper has appeared since this correlation which accepts the existence of glaciation in Britain at 2.47Ma (Donovan 1995). The earliest reliable evidence for Cenozoic glaciation in northern Europe is in the North Sea fan at 1.1Ma (Sejrup *et al.* 1995).

Recent data have been published concerning the age of the sequences at Court Hill/Kenn in north Somerset and in the Vale of Moreton, the nearest undoubted glacial sequences to Stonehenge. Current opinion places the Moreton Drift as part of the Wolston Formation on lithostratigraphic grounds, which is in turn correlated with the Lowestoft Formation of East Anglia and therefore Anglian in age (D. Maddy, pers. comm. 1996; Rose 1987, 1991).

In 1984 Andrews *et al.* (1984) published aminostratigraphic (AAR) data from the interglacial sediments overlying the glacial sequence at sites in and around Kenn. These fluvial, estuarine and marine sediments had previously been correlated with the Ipswichian temperate stage on pollen-stratigraphic grounds (Gilbertson and Hawkins 1978b; Hunt 1981), suggesting that the glacial sediments were pre-Ipswichian and probably Wolstonian in age. Though AAR data from *Macoma*, *Corbicula* and *Patella* from the Kenn Church and New Blind Yeo Drain sites supported correlation with oxygen isotope stage 5e (Ipswichian; Table 1), ratios on *Corbicula* from the Kenn Pier and Yew Tree Farm sites suggested that these riverine deposits are significantly older and correlated with 'Group IV' sites such as Purfleet in the Thames Estuary. Andrews *et al.* (1984) suggested a date of between 400 and 600k for these riverine deposits and concluded that the underlying glacial deposits must be older. This led Bowen and Sykes (1988) to infer that the glacial sediments were deposited in oxygen isotope stage 12 ('Anglian'; Table 1), but later Bowen *et al.* (1989) revised the correlation of the interglacial sediments to stage 15, confirmed in Bowen (1994): 'The aminostratigraphic method of Bowen *et al.* (1989) would correlate the Kenn Pier beds with . . . oxygen isotope stage 15 (600ka). The underlying glacial deposits may, therefore, be time-equivalent to oxygen isotope stage 16 . . . which the oxygen isotope signal shows was one of the largest ice-volume episodes of the Middle Pleistocene' (op. cit., 211).

There are a number of significant problems with these aminostratigraphic data and their interpretation. First, a number of methodological problems have emerged with respect to the AAR method as applied to molluscs. These have been described by Bowen *et al.* (1989) as 'diagenetic artefacts' and include analytical complications, sample contamination during diagenesis or analysis which lowers the D/L ratio, and leaching of free amino acids. To these may be added intra-shell diagenetic effects (Sejrup and Haugen 1994) which can cause D/L ratios to vary across an individual shell with amplitudes consistent with aminostratigraphic groups relating to different glacial-interglacial cycles. A second major problem is reworking causing mixing of samples of different ages during sedimentation. The known effects of reworking in generating mixed age populations (Bowen and Sykes 1988) should caution against correlation of sites on the basis of only a few shells, as in the Kenn case. These fundamental problems perhaps illuminate some specific inconsistencies with regard to the Kenn data. *Corbicula* remains unknown from any other well-established 'Cromerian Complex' (Table 1) site in the British Isles (R.C. Preece, pers. comm. 1996) suggesting that these age ascriptions are at least surprising. The correlation with Purfleet is a major problem because not only is it extremely well established that the Thames was not occupying this part of the valley during the pre-Anglian Pleistocene (Gibbard 1994; Bridgland 1994) but there is a wealth of independent biostratigraphic data to suggest that the interglacial beds here are much younger than the 'Cromerian Complex' (Bridgland *et al.* 1995). The age interpretation of the AAR data from Purfleet must therefore be incorrect.

The latitude with which AAR ratios can be interpreted in terms of age, as demonstrated in this instance, invites homotaxial error. Bowen (1994) has reinterpreted the correlation of the Kenn AAR data not on the basis of the data themselves but simply because the positive isotopic excursion of stage 16 is large and therefore suggests major glaciation. This procedure amounts to a simple pigeonholing of deposits into an external reference model. Its invalidity is demonstrated by the fact that whereas the oxygen isotope record is a measure of global ice volume, during the maximum of the Last Glacial Maximum (LGM; Table 1) the British ice sheet volume was equivalent to a lowering of glacio-eustatic sea-level by 0.91 m (Boulton *et al.* 1977), and therefore constituted 0.76% of the global ice mass difference between the LGM and the present day. Given the insignificance of this contribution of the British ice mass to the oxygen isotope record perhaps more attention should be paid to establishing the age of British glacial deposits by multiple and reliable methods rather than simply using the deep sea oxygen isotope stages as a convenient set of stratigraphic labels. This would assist in the analysis of hysteresis between the marine and terrestrial records, which may in turn demonstrate important causal feedback mechanisms in the climate system.

All that can therefore be stated with certainty about the age of the Kenn glacial sequence is that it is pre-interglacial and therefore pre-Ipswichian in age.

Conclusion

The hypothesis that the Stonehenge bluestones were transported by ice to the Wiltshire Downs is not consistent with current glaciological or glacial geological theory or observational data. The bluestone lithological assemblage is, however, absolutely consistent with derivation from a glacial drift source in Pembrokeshire; this is supported by the limited evidence for striae on some of the undressed bluestone surfaces. If the ^{36}Cl date is accepted, this might suggest that such a source was of Late Devensian age. Thomas' view (1923) that the boulders were '... taken from the boulder-strewn slopes on the immediate south and south-east of the Prescellys between Carn Meini and Cil-maen-llwyd where all the types have been collected together by glacial action' (op. cit., 251) remains unchallenged, as do his principal objections to the glacial transport hypothesis: apart from the ice-marginal sites in north Somerset, nowhere between South Wales and Stonehenge, is there '... evidence of glaciation of an intense character. There are no trains of far-travelled boulders, no ice-scratching and polishing of outstanding rocks, and no thick accumulations of boulder clay ... such a hypothetical ice-sheet, in order to account for the Foreign Stones of Stonehenge would have to gather from Pembrokeshire blocks all of about the same size and mainly of two rock-types. It would have to carry them all that distance without dropping any by the way. Further, it would have to pass over all kinds of rocky obstacles without gathering to itself any of the various materials over which it was forced to ride' (op. cit., 254).

The common element which unifies all advocates of the glacial hypothesis is incredulity that these stones could have been transported from Pembrokeshire to Wiltshire by prehistoric man. This centres around the copious bluestone fragments found on-site and was first expressed by Judd (1902): '... it is quite inconceivable that they [the bluestones] should have been hewed and chipped ... and reduced in some cases to half their dimensions, *after having been carried with enormous difficulty over land and water, and over hills and valleys*' (Judd's italics, p. 117). Kellaway expresses a similar view in 1971: '... the motives for conveying them ... to Stonehenge while ignoring local resources are incomprehensible' (op. cit., 34). In the light of this disbelief a mass of extremely circumstantial evidence has been marshalled into an hypothesis which in its totality has some apparent credibility but whose component parts are either capable of alternative explanation or equivocal or non-existent. As Sherlock Holmes said to Watson: 'How often have I told you that when you have eliminated the impossible, whatever remains, *however improbable*, must be the truth.'

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some elements of the physical record of Stonehenge are offered and suggestions are made for the future direction of experimentation.

C. P. GREEN

The provenance of rocks used in the construction of Stonehenge

The geological evidence in Wiltshire gives no support to the view that the stones forming Stonehenge were found by its builders close to the site of construction. The presence of suitable sarsen stones near Stonehenge in the Early Bronze Age is indicated neither by the geological history of the area nor by the present-day distribution of sarsens. The absence of glacial or glacially-derived material on Salisbury Plain makes it unlikely that glacial ice carried the bluestones of Stonehenge from the Preseli Hills to Wessex. The history of the bluestone supposedly found in Bowls Barrow is reviewed.

J. D. SCOURSE

Transport of the Stonehenge bluestones: testing the glacial hypothesis

Two principal mechanisms have been invoked to explain the transport of the far-travelled bluestones used in the Stonehenge monument from their source region in Pembrokeshire: by glacier or by man. Glaciers have been thought to represent the only natural agency capable of transporting boulders of the size of the bluestones over the distances required, and this mechanism has periodically received serious attention since it was first proposed by Judd in 1902. There are two current propositions invoking transport of the bluestones by ice; Thorpe *et al.* (1991) envisage Anglian ice flowing eastwards from Pembrokeshire across South Wales and into central southern England, whilst Kellaway (1991a, 1991b) suggests deposition from the north in association with a Pliocene glaciation at 2.47Ma. The glacial hypothesis is critically tested by addressing four issues: the physical principles underlying the entrainment and transport of large boulders by glaciers; the occurrence/absence and implications of diagnostic surface microwear and particle shape characteristics of the bluestones; the Pleistocene stratigraphy and geomorphology of southern England and adjacent shelves; and the glaciological plausibility of a source trajectory from Pembrokeshire. It is demonstrated that though glaciers are capable of transporting erratic boulders many thousands of kilometres irrespective of bed topography, the particular case posed by the Stonehenge problem is not compatible either with the mechanics of ice flow or with the geological evidence. The weight of the current available evidence strongly indicates that the Stonehenge bluestones were not transported by ice from Preseli to Salisbury Plain.