

Submission of Hartfell Score (south Scotland) as a GSSP for the base of the middle stage of the Upper Ordovician Series

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Location: north of Moffat in the southern Uplands of Scotland (Figure 1). The proposed section (NGR NT 097 117) lies in the well-exposed valley-side crag section of Hartfell Score.

Access (taken from Rushton, 1993): the section lies within open access countryside, a visit involving 5 to 6 km of easy walking on a public footpath. Warm and waterproof clothing is desirable, in view of the exposed nature of the terrain and the notorious fickleness of Scottish weather. From the centre of Moffat (Figure 2) one heads north on the road to Edinburgh (A701), but after about 400 m, near the church, where the main road swings left out of the town, one takes the minor road (ultimately a dead end) that continues northwards to Ericstane (Fig.2). After 5 km the road crosses Auchencat Burn; here there is limited parking space by a large red

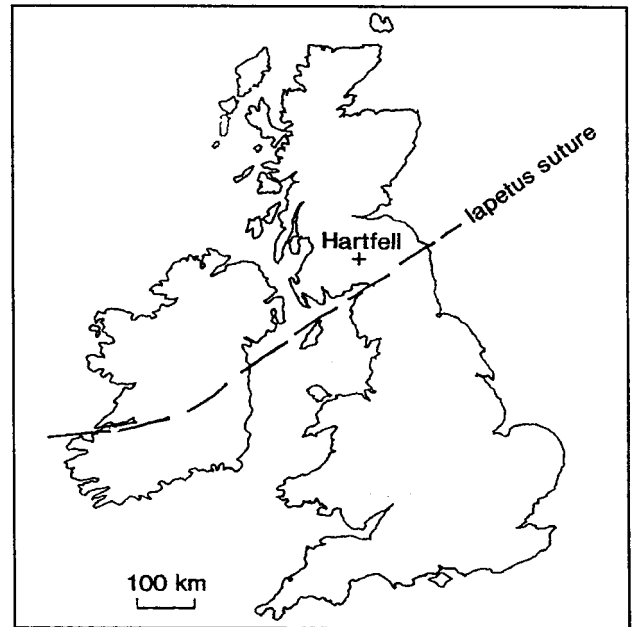


Figure 1: Location of Hartfell Score within the UK (adapted from Zalasiewicz *et al.* 1995).

corrugated iron building south of the bridge. Just north of the bridge a public footpath is signposted eastwards to Hartfell Spa; the way is marked by the occasional confidence-post. The path follows Auchencat Burn upstream, but lies well above the north bank. After nearly a kilometre there is a gash in the hill that is Hartfell Score (NT 097 117). North-west of the hill-fort the burn occupies a gorge with a waterfall at the head (Frizles Burn); at this place in the gorge, upfaulted Lower Birkhill Shales are overlain by Gala Group greywackes. The path stays high above the burn to the head of Frizles Linn, but just beyond it descends to the bank by a series of well-made steps. The path remains on the north bank and follows roughly the line of the fault that brings up the Hartfell Inlier. Half a kilometre upstream, on the south bank, is the site of a trial adit for copper minerals, associated with an exposure of green-stained Birkhill Shales. After a further half-kilometre, Auchencat Burn swings away to the right, but the path continues north-eastwards, parallel now with a tributary, the Spa Well Burn; and the Hartfell Spa itself is reached about 1.5 km from the steps. The chalybeate (iron-containing) waters of Hartfell Spa were declared beneficial by John Williamson in 1748; the well is now enclosed and sheltered by a small stone building. An excellent view of the main sector of Hartfell Score (Figure 3), including the proposed stratotype, is obtained from a point 100 m or so upstream from the spa.

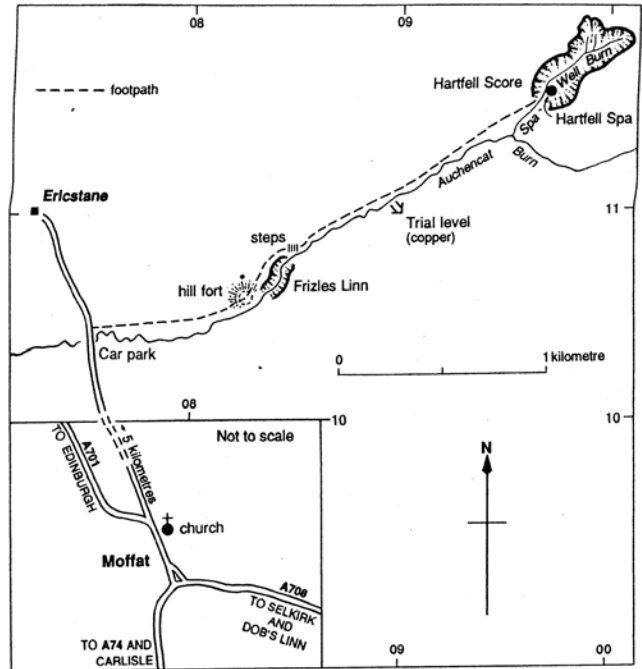


Figure 2: Detailed location map showing access to Hartfell Score (from Rushton 1993).

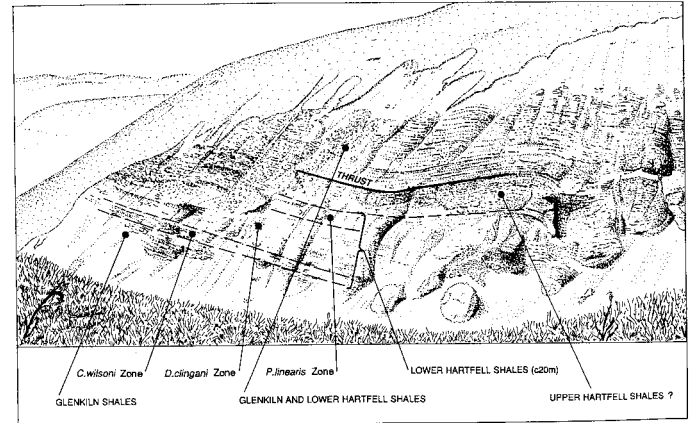


Figure 3: Sketch of main face at Hartfell Score (from Rushton 1993).

Geological and structural setting (1): the Southern Uplands: The proposed succession forms part of the late Ordovician to early Silurian strata of the southern Uplands of Scotland, which can

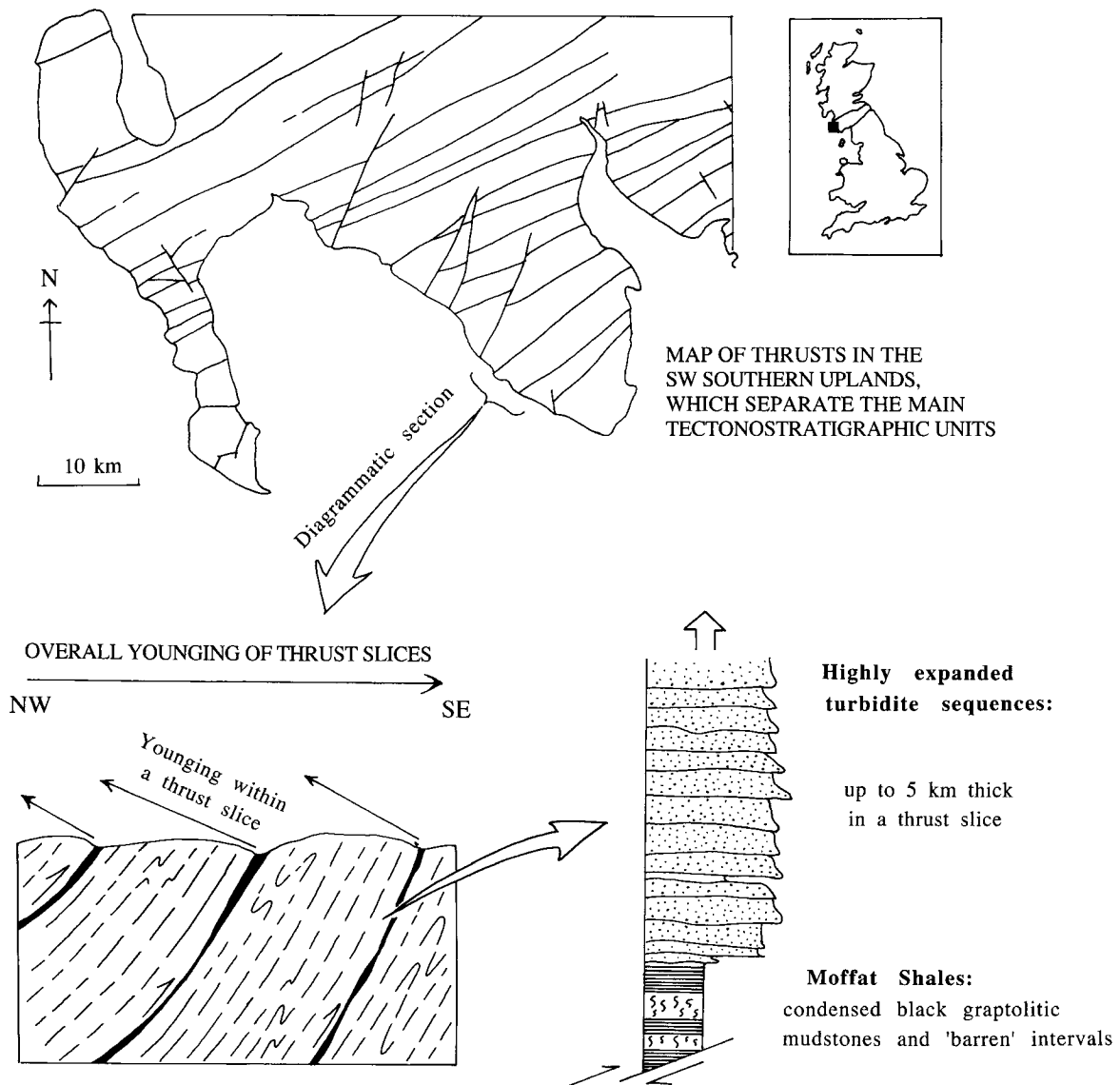


Figure 4: Architecture of the southwestern part of the Southern Uplands accretionary prism of Scotland (from Zalasiewicz 2001, in part after Rushton *et al.* 1996).

claim to be the cradle of graptolite biostratigraphy. Charles Lapworth's (1878) pioneering use of these fossils in working out the geological structure of this region was revolutionary in its day,

and propelled the graptolite biostratigraphy into its current position as one of the most useful tools in Early Paleozoic geology.

The Southern Uplands is a belt of steeply dipping to vertical rocks, some 200 m along strike by 60 km across, largely comprising unfossiliferous greywackes, with scattered mudstone intervals (Figure 4). In the middle of the last century, there was intense debate as to whether these rocks formed a single, immensely thick sequence, or a thinner sequence that had been structurally repeated. Charles Lapworth showed that the graptolites (hitherto an obscure group, thought to be of little use for correlation) in the mudstones could be grouped into a succession of fossil zones, and the regional correlation of these zones clearly indicated that multiple tectonic repetition of the strata had taken place. The use of graptolites as geological time-keepers was, then, neither obvious nor uncontroversial. Joachim Barrande, in Bohemia, had carefully described graptolite assemblages (1850), but interpreted their repetition within rock sequences as the result of successive colonization events, and not the effects of tectonic structure. (Subsequent study ultimately proved Barrande wrong, but at the time his ideas seemed sensible and, indeed, they foreshadow modern biofacies models.)

More recent work in the Southern Uplands (e.g. Leggett, McKerrow & Eales, 1979; Rushton, Stone & Hughes, 1996) has elaborated the sedimentary and structural history considerably. These successions are now known to be characterized by remarkable, inter-related patterns of sedimentological, biostratigraphic and structural data. The use of way-up criteria demonstrated that the structural repetition was achieved largely by thrusting (Figure 4), and not by folding as Lapworth had supposed. These thrust slices consistently dip steeply to the NW. The main body of each comprises medium- to coarse-grained greywackes, commonly arranged in stacked, fining-upwards units 1-2 m thick comprising Bouma divisions Tabc or Tbc. Along the SE (lower) margins of most thrust slices there are thin (few 10's of metres) sequences of siliceous mudstones and cherts of the Moffat Shale Group, which acted as a decollement plane during the thrusting. These are commonly dark-coloured, and include an abundant fauna of graptolites, though other macrofossils are rare. Among microfossils, radiolaria are abundant and chitinozoa have been recovered (see below).

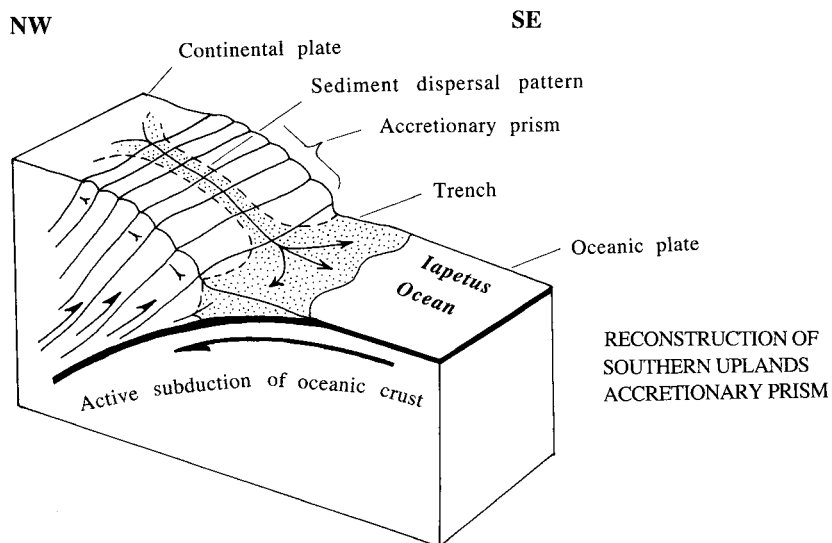
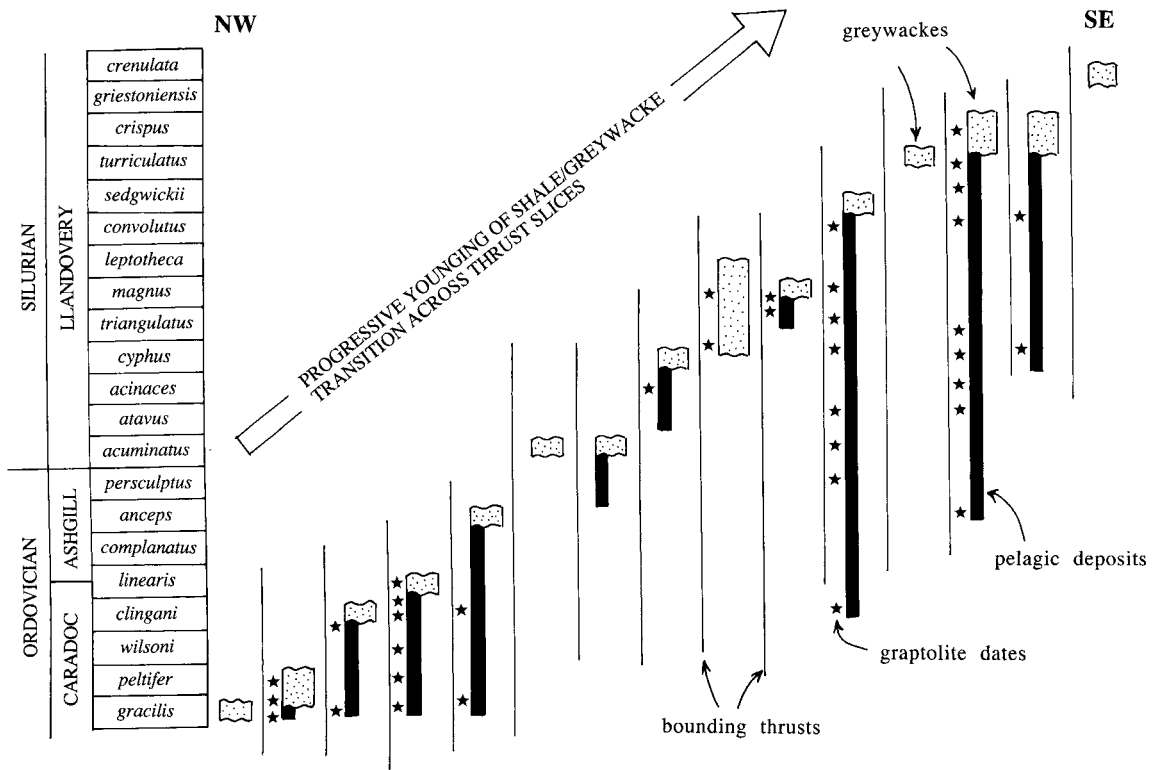


Figure 5: Graptolite biozonation of the southwestern part of the Southern Uplands accretionary prism, showing diachronism of the transition between pelagic shales and greywackes across thrust boundaries; and reconstruction of the accretionary prism (from Zalasiewicz 2001, after Stone, 1995).

Analysis of the graptolites between thrust slices showed an overall younging direction for each thrust slice (or, more precisely, of the transition from mudstone to greywacke sedimentation in each thrust slice) from NW to SE. The strata within each individual thrust slice, though, young in the opposite sense, from SE to NW (Figure 5).

This overall spatial and temporal geometry has been interpreted as representing the construction of an accretionary prism (Figure 5). The Moffat Shales represent slowly accumulating pelagic and hemipelagic (partly radiolarian) oozes on a deep ocean floor, the common presence of fossilized plankton (graptolites) associated with a lack of benthos or bioturbation indicating sea floor anoxia. Pale 'barren' beds are interbedded with the dark graptolitic mudstones and indicate episodes of sea floor oxygenation. These sites of distal, oceanic-style sedimentation were progressively moving NW-wards, carried on a subducting oceanic plate towards a landmass which was shedding large amounts of sedimentary debris (the greywackes) into a trench. Each site would be thus be buried beneath thick turbiditic greywackes, and then would be obducted, as the oceanic crust was subducted beneath the continental landmass.

The close biostratigraphic dating allows an estimation of the rate of sedimentary and tectonic processes: approximately 1-2 graptolite zones - i.e. ca 1 million years - per thrust slice) and the geometry of thrusting (the stacks show an orderly pattern of thrusting at the SW end of the thrust belt, but include out-of-sequence thrusts to the NE, possibly as a result of an obstacle to thrust-propagation there - Rushton, Stone & Hughes, 1996).

Geological and structural setting (2): Hartfell Score

As is frequently the case in the infaulted inliers of Moffat Shales, the south-east (right-hand going upstream) side of the inlier is strongly deformed; at Hartfell this side is composed, at least partly, of Lower and Upper Birkhill Shales, but it is very difficult to interpret the stratigraphy in detail.

The north-west side of the exposure, however, is much more coherent (Figure 6). Though complicated by thrusting, the general succession is as follows (Rushton, 1993):

Upper Hartfell Shales	grey 'barren' mudstones	Ashgill
Lower Hartfell Shales	black graptolitic mudstones	Caradoc
Glenkiln Shales	grey mudstones and cherts	Llandeilo

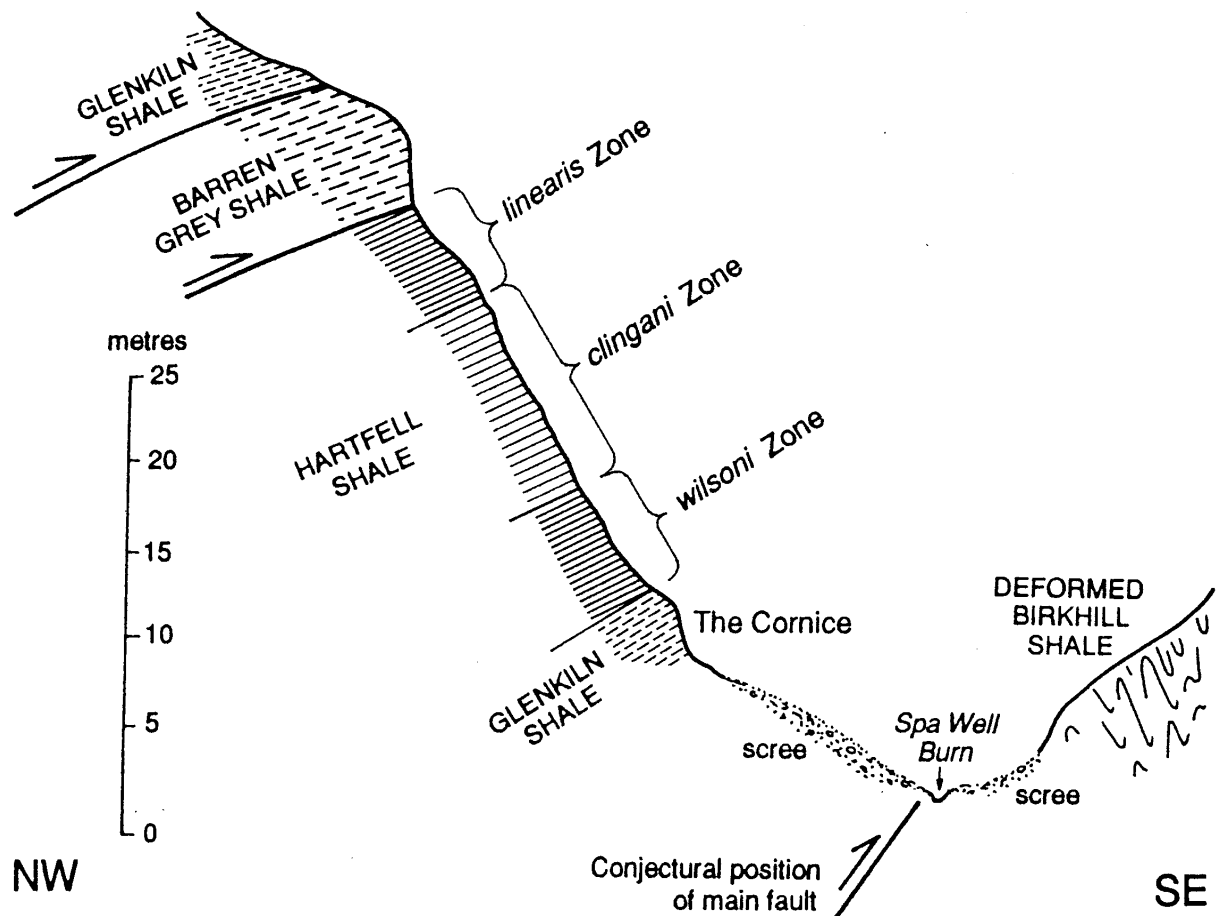


Figure 6: Sketch section through the Main Cliff, Hartfell Score (from Rushton 1993).

The north-west Main Cliff (Figure 3) can be well viewed by ascending the cliff on the opposite side of the burn. It approaches 500 m in length and 70 m in height. The lower slopes are covered by scree, but higher up the beds are well exposed, dipping into the cliff at about 40 degrees and striking along the cliff. The screes at the foot of the cliff include many graptolite-bearing blocks, and provide a good indication of the richly fossiliferous nature of this succession (Figure 7). For stratigraphically controlled specimens it is necessary to ascend the Main Cliff,

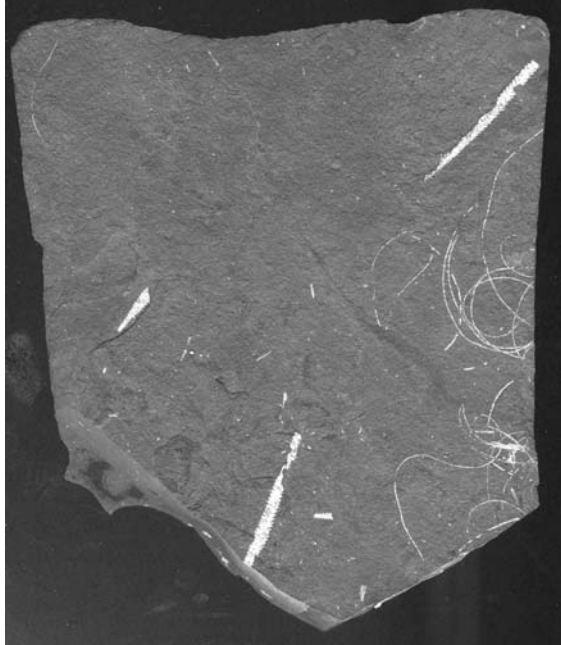


Figure 7: Typical block of graptolite shale from Hartfell Score, illustrating the nature of the preservation (graptolites seen as white mica strain fringe overgrowths on flattened periderm).

which is not excessively steep and can be studied at many points. Systematic collection of material is eminently possible, and we see no threat to this accessibility in the future.

The succession is clearly repeated more than once. Early workers considered these repetitions to be brought about by folding, but more recently imbricate thrusting has been preferred to account for the structure. Lapworth, who originated the hypothesis of isoclinal folding in the Southern Uplands, did recognise that one limb of each isocline here was faulted out. The main graptolitic section comprising a little over 20 m of black graptolitic mudstone representing the *wilsoni*, *clingani* and *linearis* Biozones, is overlain by barren grey mudstones, the contact

being a thrust-fault. The grey mudstones are in turn overlain by thrust imbricate repetitions of the graptolitic Hartfell Shales. No significant tectonic breaks have been recognized within the main section studied, despite signs of minor disturbance.

Hartfell Score - history of Research: Hartfell Score is one of the largest exposures in the Moffat Shales of southern Scotland, and is the type area for Lapworth's Hartfell Shales division of the Moffat Shales. The exposure has been described in some detail by Lapworth (1878, pp. 292-296), Peach & Horne (1899, pp. 134-137) and Rushton (1993, pp. 173-179).

This section was one of the most important used by Lapworth (1878) and Elles & Wood (1901-18) in constructing the zonal scheme for the Caradoc, though little further detailed work was done until the systematic graptolite biostratigraphical study of Zalasiewicz, Rushton & Owen (1995). Complementary studies have been carried out by Williams on the *clingani* and *linearis* Biozone graptolite faunas of the nearby Dob's Linn section (1982) and on the *wilsoni* Biozone of

the Southern Uplands (1994), in part based on material from Hartfell Score. More recently, the section has been sampled for chitinozoa (Vandenbroucke, this account).

Hartfell Score and the surrounding area currently form part of a survey and research programme by the British Geological Survey, with modern geological maps at 1:50 000 scale in press; Hartfell Score itself lies on 1:50 000 Sheet 16 (West) – Moffat, due to be published around 2006. The BGS work has formed part of, and helped stimulate, a wider body of current research exemplified by recent volumes in the *Scottish Journal of Geology* (2003, volume 39, part 1) and the *Transactions of the Royal Society of Edinburgh* (2001, volume 91, parts 3 and 4).

Hartfell Score is an extremely valuable section in the Moffat Shales, with an excellent Caradoc succession as well as being one of the most north-westerly inliers with good Birkhill Shales (topmost Ashgill - Llandovery). These inliers of Moffat Shales are critical to delineating the thrust slices in the BGS mapping model of the Southern Uplands, particularly, as here, where the greywackes in adjacent tracts are petrographically indistinguishable. Taken together, Hartfell Score and Dob's Linn are probably the two most valuable Moffat Shale Group localities in the Central Belt of the Southern Uplands and are type sections for the Hartfell Shales and Birkhill Shales respectively. Though the Hartfell section is indeed tectonised to some degree, there are other sections nearby, such as Dob's Linn, Garpol Linn, Cow Linn, and so on which, studied as a group, can be used to test any stratigraphy erected at Hartfell and to minimise the possible effects of tectonic excision of significant parts of the succession

Succession of graptolite faunas (and see graptolite range-chart: Figure 8):

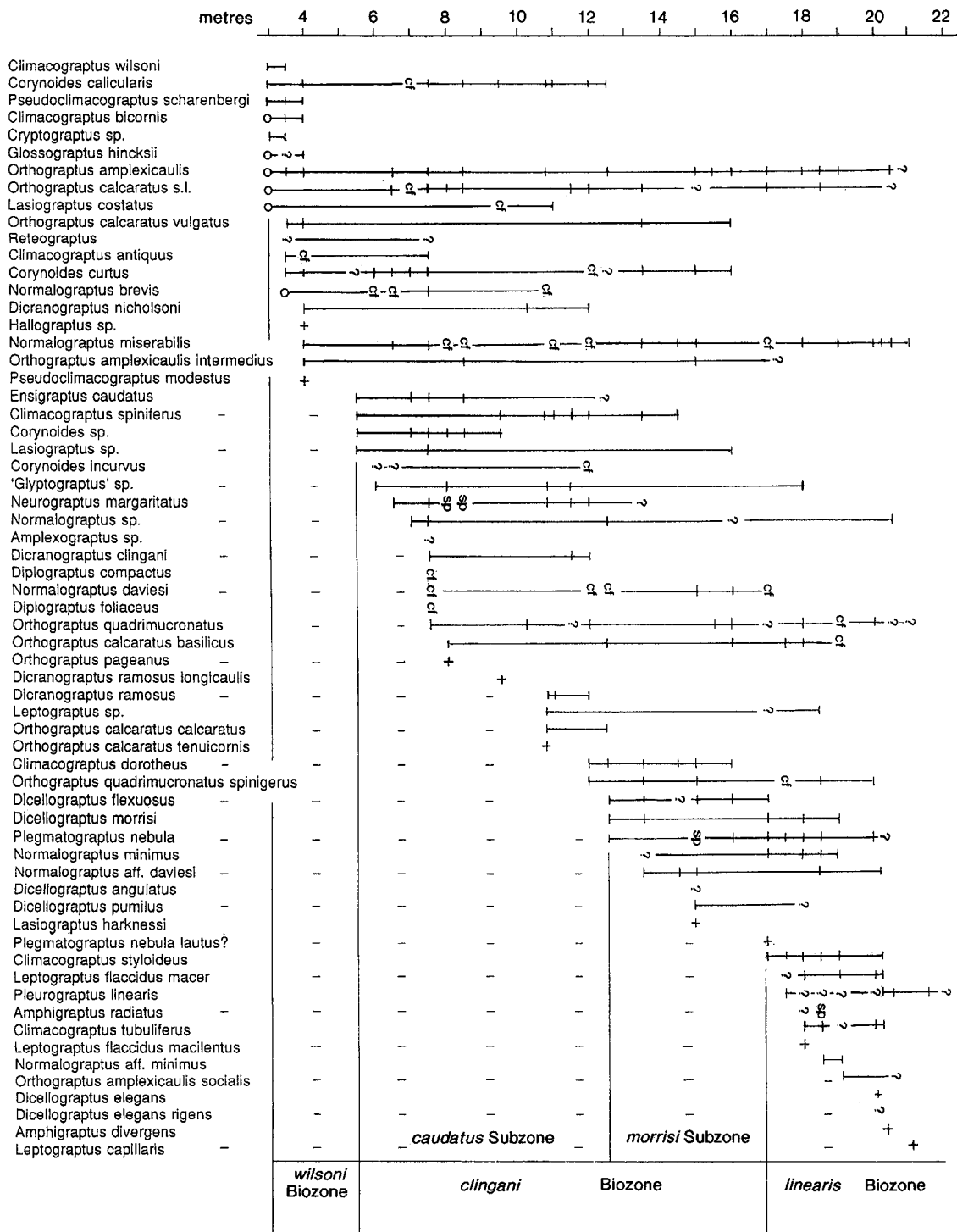


Figure 8: Ranges of graptolite taxa in the measure section of Hartfell Score, southern Scotland, taken from Zalasiewicz *et al.* (1995). Circles in the *wilsoni* Biozone indicate additional records kindly furnished by Dr. S.H. Williams.

(1) **wilsoni Zone:** upstream of the spa well the pale hard beds of the Glenkiln Shales are overlain by dark platy mudstones with occasional fossiliferous seams, these representing the *wilsoni* Biozone. Graptolites from 3.0 to 4.0 m above the base of the measured section (Fig. 8) include the locally abundant *Climacograptus wilsoni* and *C. bicornis*, with *C. antiquus*, *Pseudoclimacograptus modestus*, *P. scharenbergi* and *Glossograptus hincksii*. These species are typically of pre-*clingani* Biozone horizons. They are associated with longer-ranging taxa such as *Corynoides* species, occurring as swarms, and *Orthograptus* of the *amplexicaulis* and *calcaratus* groups.

(2) **clingani Biozone, Ensigraptus caudatus Biozone:** 5.5 m above the base of the section, in hard black mudstones, *Ensigraptus caudatus* and *Climacograptus spiniferus* appear, while a little higher in the section, *Dicranograptus clingani*, '*Glyptograptus*' *daviesi*, *Orthograptus pageanus* and *O. quadrimucronatus* subspp. have been recorded.

(3) **clingani Biozone, Dicellograptus morrisi Subzone:** this is a partial-range subzone recognized by the range of *D. morrisi* below the *linearis* Biozone. Assemblages between 12.5 m and 16 m show the incoming of *Dicellograptus morrisi*, *D. flexuosus* and *Plegmatograptus nebula* and, a little higher within this interval, *Dicellograptus pumilus*. These are associated with a number of species from the underlying subzone, though *D. clingani* and *E. caudatus* are absent. *Climacograptus dorotheus* is common at some levels in the *morrisi* Subzone, though it appears as a rarity at 12 m, where it is associated with *C. spiniferus*.

(4) **linearis Biozone:** assemblages from 17 m to 21 m are characterized by the incoming of *Climacograptus styloideus*, *C. tubuliferus*, *Dicellograptus elegans*, *Leptograptus flaccidus macer* and *L. capillaris*. *Pleurograptus linearis* occurs from 17.5 m, becoming common above 20 m. Species ranging up from the lower horizons include *Dicellograptus morrisi*, *Orthograptus quadrimucronatus*, and other *Orthograptus* species. There are thin pale beds of metabentonite in this biozone.

Chitinozoans (and see range chart (Figure 9) and correlation chart (Figure 10))

32 samples from the Hartfell Score section have been processed for chitinozoans (Figure 11). A number of samples were barren or contained only long-ranging chitinozoans, and the chitinozoans that were found tend to be heavily pyritized and poorly preserved. However, the samples that yielded the most promising chitinozoans are situated immediately above and below the boundary between the *wilsoni* and *caudatus* biozones, and these have provided stratigraphically useful data that complement that obtained from the graptolites:

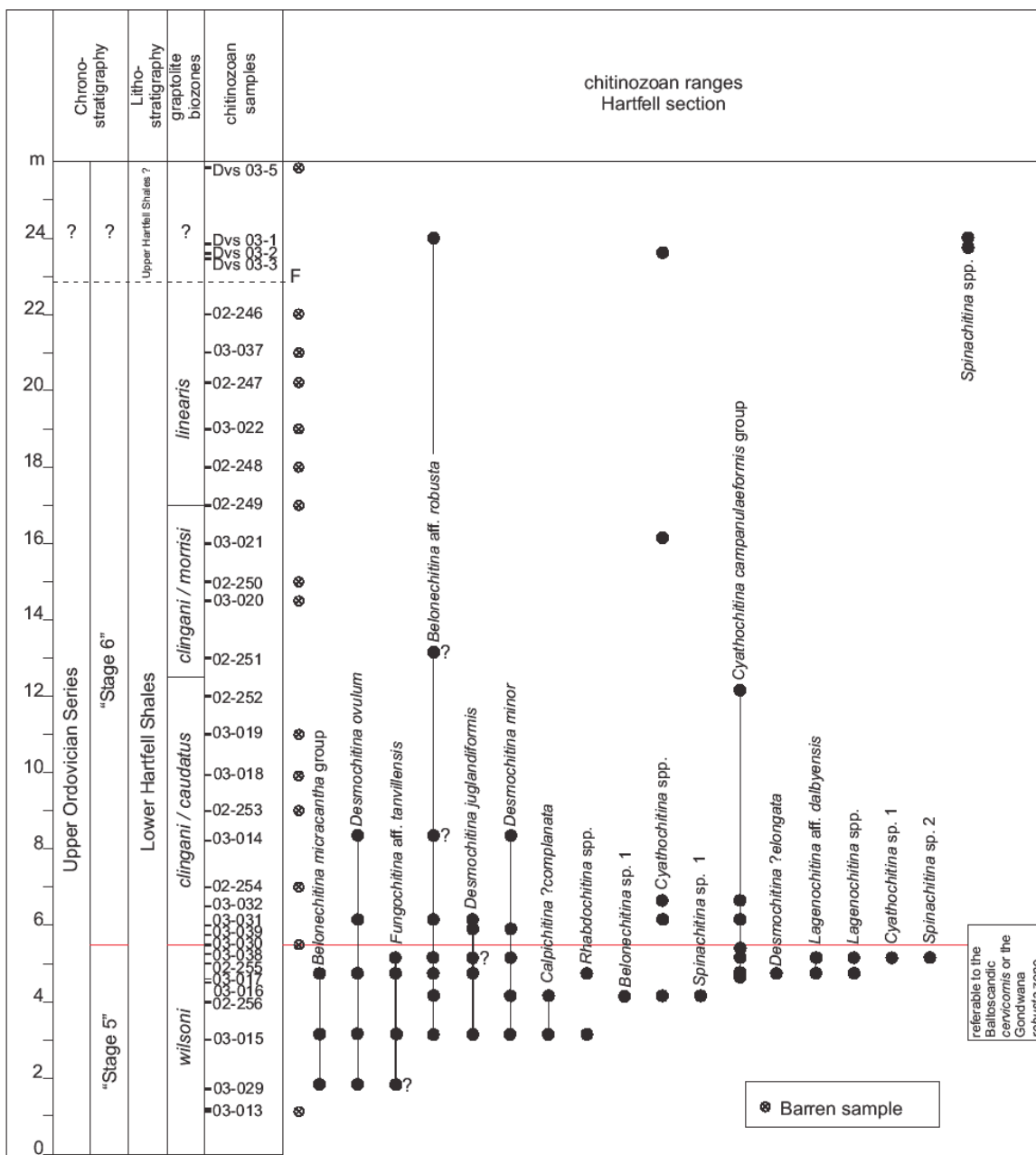


Figure 9: Chitinozoan ranges at Hartfell Score.

- Five samples between 3 m and 6 m above the base of the section yielded *Desmochitina juglandiformis*. This species has been reported from Baltoscandia as an accessory species in the *S. cervicornis* Biozone (Nölvak & Grahn, 1993). In the correlation scheme by Webby *et al.* (see chart), this *cervicornis* Biozone is placed from the middle *foliaceus* to the middle *clingani* Biozone, thus agreeing extremely well with the graptolite data from Hartfell Score.

CHRONO STRAT	Graptolites			Chitinozoans				TIME SLICE							
	BRITAIN			BALTO SCANDIA		N GONDWANA									
UPPER ORDOVICIUM SERIES	6	ASHGILL	Hir	<i>persculptus</i> <i>extraordinarius</i>	HARJU	Po	<i>scabra/taugourdeau</i> <i>gamachiana</i>	ASHGILL	<i>oulebsiri</i> <i>elongata</i>	6c					
			Ra	<i>pacificus</i> <i>anceps</i>		Pi	<i>rugata</i>		<i>merga</i>	6b					
			Ca	<i>complexus</i>					<i>nigerica</i>	6a					
			Pu	<i>complanatus</i>		Vo	<i>bergstroemi</i> <i>barbata</i>		<i>barbata</i>						
			5	CARADOC		St	<i>linearis</i>		Na	VIRU	fungi- formis	CARADOC	<i>fistulosa</i>	5d	
						Ch	<i>clingani</i>		Rk				<i>reticulifera</i> <i>augusta</i>	<i>robusta</i> ?	5c
						Bu	<i>foliaceus</i> (= <i>multidens</i>)		Oa				<i>Anc. sp. 1</i> <i>multiplex</i>	<i>tanvillensis</i>	
	Au	<i>gracilis</i>			Ke	<i>cervicornis</i> <i>dalbyensis</i> <i>curvata</i>	??	5b							
					Ha	<i>rhenana</i> <i>stentor</i>	<i>deunffi</i>	5a							
					Ku		<i>ponceti</i>								

■ range of *D. juglandiformis* in Baltoscandia (Nölvak and Grahn, 1993) and in Northern Gondwana (Paris, 1990)

Figure 10: The range of the chitinozoan species *Desmochitina juglandiformis* on Baltoscandia (Nölvak & Grahn, 1993) and on Northern Gondwana (Paris, 1990), compared to the British graptolite biozonation, as correlated on the most recent Webby *et al.* (2004) correlation charts.

D. juglandiformis has also been reported to have a very limited range on Gondwana, but only from one location in Spain (Paris 1990), within the *B. robusta* Biozone. This is stratigraphically slightly higher than the *S. cervicornis* Biozone on Baltoscandia, according to the Webby *et al.* scheme. Paris (1990), however, left open the possibility of that the *tanvillensis* and *robusta* zones are stratigraphically slightly earlier than originally proposed, given the elasticity of the original stratigraphic constraints on them.

- Within the *wilsoni* Biozone, several samples yielded a species of *Fungochitina* which is closer to *F. tanvillensis* (an index fossil on Gondwana) than to *F. fungiformis* (the index fossil of the Baltoscandian zone immediately above the *S. cervicornis* Biozone). It is kept in open nomenclature in this account, as *F. aff. tanvillensis*, because the poor preservation does not allow comparison of the ornamentation on the vesicle wall with that on the type material, and because the Scottish specimens are slightly smaller than the type material. The presence of a typical Gondwana form on the Laurentian margin is surprising, given recent palaeogeographic reconstructions. However, the presence of this *Fungochitina* suggests that the level represented here is high rather than low in the *cervicornis* Biozone (no *Fungochitina* species being known on Baltoscandia below the *F. fungiformis* Biozone (Nölvak, pers. comm.)).

Other chitinozoans, such as *Desmochitina ovulum*, *Calpichitina complanata?* and representatives of the *Cyathochitina campanulaeformis* and *Belonechitina micracantha* groups are known to have longer ranges within the Late Ordovician.

In summary, the level around the *wilsoni-caudatus* boundary, and hence the level of the proposed GSSP, can be assigned to the Baltoscandian *S.cervicornis* Biozone (using the range of *D. juglandiformis*) and, most probably, high rather than low in that zone. The same fossil allows correlation with the Gondwana biozonation (*B. robusta* Biozone).

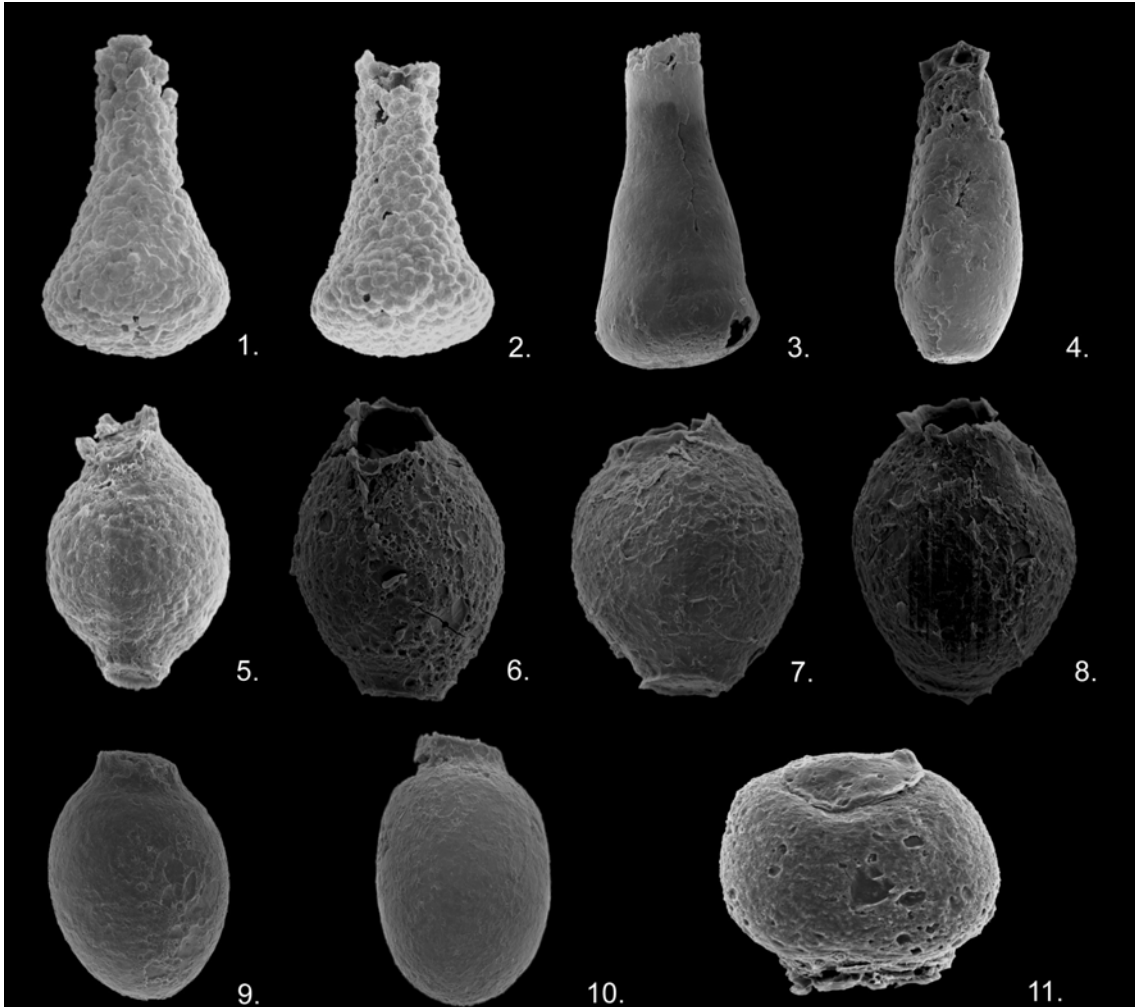


Figure 11: Chitinozoans from Hartfell Score.

All measurements in microns (L x Dp x Dc or Dp x Dc). Abbreviations, see Paris (1981): L= total length, Dp= chamber diameter, Dc= diameter of oral tube.

1. *Fungochitina* aff. *tanvillensis* sample TVDB 03-015 (75-60-25)
2. *Fungochitina* aff. *tanvillensis* sample TVDB 03-015 (100-70-30)
3. *Spinachitina* sp. 2 sample TVDB 02-255 (140-70-35)
4. *Lagenochitina* aff. *dalbyensis* TVDB 02-255 (140-55-30)
5. *Desmochitina juglandiformis* TVDB 03-015 (100-75-30)
6. *Desmochitina juglandiformis* TVDB 03-031 (105-80-30)
7. *Desmochitina juglandiformis* TVDB 03-031 (90-70-30)
8. *Desmochitina juglandiformis* TVDB 03-031 (90-75-30)
9. *Desmochitina ovulum* TVDB 03-017 (100-75-35)
10. *Desmochitina ovulum* TVDB 03-017 (100-70-35)
11. *Calpichitina* ?*complanata* TVDB 03-015 (80-40)

Discussion

Advantages: The Hartfell Score section offers a continuously exposed section through fossiliferous deep marine strata that include the base of the *clingani* Biozone. Points in favour of it as a potential GSSP are:

- its good accessibility, with plenty of along-strike exposure.
- the abundant and diverse (cf. Finney & Berry 1997), eminently correlatable graptolite fauna, almost all the graptolites being well figured in Elles and Wood's (1901-1919) monograph; many of the specimens could be ranked as topotypes as several of the taxa originated from Hartfell Score. Compilations of UK graptolite ranges in progress (Taylor *et al.* in preparation) and of taxonomic information (e.g. Zalasiewicz *et al.* 2000) will further enhance the usefulness of the Hartfell data. Ultimately, of course, there is a practical limit to the resolution offered by graptolite biostratigraphy (Signor & Lipps 1982), hence the need for a variety of correlation methods, as discussed below.
- There are also intermittent, but useful chitinozoan assemblages, especially so around the proposed boundary level. Potentially, the radiolarian assemblages may also offer correlative potential.
- More speculatively, as a deep marine, finely laminated succession of essentially hemipelagic origin, laid down within continuously anoxic conditions within the interval in question, it potentially offers a high-resolution record of climatically/oceanographically-controlled sedimentation events, comparable to those recognized in much younger strata such as those of the current Santa Barbara Basin off California (Thornton 1984). By comparison with more recent deposits, closer analysis may well yield signatures such as those generated by Milankovitch insolation patterns, patterns which provide a remarkable high-resolution stratigraphy that now provide the basis for Quaternary and Tertiary chronostratigraphy (e.g. Shackleton *et al.* 2000, Sierro *et al.* 2000), and which are being currently investigated and exploited in Mesozoic strata (Gale *et al.* 1999; Jenkyns 1999)). Currently, the absence of

Milankovitch signals would be regarded as a serious weakness in any potential post-Palaeozoic candidate GSSP. While Milankovitch signals have not yet been significantly exploited in early Paleozoic deposits, the potential for such stratigraphy undoubtedly exists, the extension of this technique into ever older rocks is proceeding apace, and the Hartfell Score section is of suitable facies for such analysis to be attempted.

- In a related and analogous fashion, the Hartfell section is amenable to investigation as regards the possibility of a carbon isotope stratigraphy (cf. Brenchley *et al.* 1994; Underwood *et al.* 1997)), both by means of whole-rock kerogen and by means of analysis of the C isotope composition of graptolite periderm, a technique currently being developed (Page, Zalasiewicz) to counter the effects of factors (e.g. mixed provenance) that hinder the use of whole-rock compositions.
- As regards radiometric dating, the section contains bentonite horizons with potential for the U-Pb dating of zircons. The Hartfell Shales at Hartfell Score also contain small, but abundant authigenic monazite nodules (Zalasiewicz, Milodowski, Fiddy, unpublished) that, by comparison with similar but larger nodules recovered from the Welsh Basin (Milodowski & Zalasiewicz 1991; Evans & Zalasiewicz, 1996; Evans *et al.* 2002) may prove radiometrically dateable, to potentially provide diagenetic ages and so minimum absolute ages for sedimentation. Furthermore, it may be possible to use rates of hemipelagic sedimentation in such successions (see Carter *et al.* 1980, Churkin *et al.* 1977) to further constrain age relationships.

Thus, the long-term potential of the Hartfell section for global correlation appears to be extremely positive.

Disadvantages: Factors hindering the immediate application of Hartfell Score as a GSSP include:

- the low-resolution biostratigraphy carried out so far, the section being sampled for graptolites at an approximately metre scale (Zalasiewicz *et al.*, 1995). Closer sampling at this

locality would undoubtedly refine the biostratigraphy, while sampling of parallel sections within the Hartfell Shales would improve estimates of reliability.

- Some major fossil groups are rare or absent, notably conodonts and shelly fossils, while the acritarch assemblages of the Moffat Shales, dominated by sphaeromorphs, do not promise to be greatly useful (Molyneux, pers. comm.).
- At some levels, the fossils (both graptolites and chitinozoans) are poorly preserved. Graptolites are mostly flattened (though some levels within the *wilsoni* Biozone include pyrite internal moulds), but are not perceptibly tectonically distorted.
- Perhaps more seriously, the location of the succession near the basal thrust plane of a major thrust slice within an accretionary prism means that unrecognised minor, though perhaps significant, tectonic dislocations might be present.

In sum, therefore: Hartfell Score includes proven, highly effective biostratigraphic data, real long-term potential as regards developing both this and emerging forms of data, a lack or paucity of some types of data and some doubts as to whether the succession is undisturbed. In practice, it currently functions as a highly effective reference section both for Scottish/Laurentian, and for Eastern Avalonian successions. We recommend it for consideration as a potential GSSP.

Acknowledgements

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References

BARRANDE, J. 1850. *Graptolites de Boheme*. Theophile Haase Fils, Prague. vi + 74 pp., pls 1-4.

BRENCHLEY, P.J., MARSHALL, J.D., CARDEN, G.A.F., ROBERTSON, D.B.R., LONG, G.D.F., MEIDLER, T., HINTS, L. & ANDERSON, T.F. 1994. Bathymetric and isotopic evidence for a short-lived late Ordovician glaciation in a greenhouse period. *Geology*, **22**, 295-298.

CARTER, R., TREXLER, J.H. & CHURKIN, M. 1980. Dating of graptolite zones by sedimentation rates: implications for rates of evolution. *Lethaia*, **13**, 279-287.

CHURKIN, M., CARTER, C. & JOHNSON, B.R. 1977. Subdivision of Ordovician and Silurian time scale using accumulation rate of graptolite shale. *Geology*, **5**, 452-456.

ELLES, G.L. and WOOD, E.M.R. 1901-19. A monograph of the British Graptolites. *Monograph of the Palaeontographical Society*, London.

EVANS, J.A. & ZALASIEWICZ, J.A. 1996. U-Pb, Pb-Pb and Sm-Nd dating of authigenic monazite: implications for the diagenetic evolution of the Welsh Basin. *Earth and Planetary Science Letters* **144**, 421-433.

EVANS, J.A., ZALASIEWICZ, J.A., FLETCHER, I., RASMUSSEN, B. & PEARCE, N.G. 2002. Dating diagenetic monazite in mudrocks: constraining the oil window? *Journal of the Geological Society of London*, **159**, 619-622.

FINNEY, S.C. & BERRY, W.B.N. 1997. New perspectives on graptolite distribution and their use as indicator of platform margin dynamics. *Geology*, **25**, 919-922.

GALE, A.S., YOUNG, J.R., SHACKLETON, N.J., CROWHURST, S.J. & WRAY, D.S. 1999. Orbital tuning of the Cenomanian marly chalk successions: Towards a Milankovitch time-scale for the late Cretaceous. *Royal Society of London Philosophical Transactions*, **A357**, 1815-1829.

JENKYNS, H.C. 1999. Mesozoic anoxic events and palaeoclimate. *Zentralblatt für Geologie and Paläontologie*, Part **1** (for 1997), Heft 7-9, 943-949.

LAPWORTH, C. 1878. The Moffat Series. *Quarterly Journal of the Geological Society of London*, **34**, 240-346.

LEGGETT, J.K., MCKERROW, W.S. & EALES, M.H. 1981. The Southern Uplands of Scotland: a Lower Palaeozoic accretionary prism. *Journal of the Geological Society, London*, **136**, 755-770.

MILODOWSKI, A.E. and ZALASIEWICZ, J.A. 1991. Redistribution of rare earth elements during diagenesis of turbidite/hemipelagite mudrock sequences of Llandovery age from central Wales. In *Developments in Sedimentary Provenance Studies* (ed. MORTON, A.C., TODD, S.P. and HOUGHTON, P.D.), *Geological Society Special Publication No. 57*, 101-124.

NÖLVAK, J. & GRAHN, J. 1993. Ordovician chitinozoan zones from Baltoscandia. *Review of Paleobotany and Palynology*, **79**, 245-269.

PARIS, F. 1981. Les chitinozoaires dans le Paléozoïque du sud-ouest de l'Europe (cadre géologique - étude systématique - biostratigraphie). *Mémoire de la Société géologique et minéralogique de Bretagne* no. 26, 1-496.

PARIS, F. 1990. The Ordovician chitinozoan biozones of the Northern Gondwana Domain. *Review of Paleobotany and Palynology*, **66**, 181-209.

PEACH, B.N. & HORNE, J. 1899. *The Silurian Rocks of Britain, Vol. 1. Scotland*. Memoirs of the Geological Survey of the United Kingdom, HMSO.

RUSHTON, A.W.A. 1993. Hartfell Score. In *Scottish Borders Geology: An excursion Guide* (eds A.D. McAdam, E.N.K. Clarkson and P. Stone), pp. 173-179. Edinburgh: Scottish Academic Press.

RUSHTON, A.W.A., STONE, P. & HUGHES, R.A. 1996. Biostratigraphical control of thrust models for the Southern Uplands of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **86**, 137-152.

SHACKLETON, N.J., HALL, M.A., RAFFI, I., TAUXE, L. & ZACHOS, J. 2000. Astronomical calibration age for the Oligocene-Miocene boundary. *Geology*, **28**, 447-450.

SIERRO, F.J., LEDESMA, S., FLORES, J-A., TORRESCUSA, S. & DEL OLMO, W.M. 2000. Sonic and gamma-ray astrochronology: Cycle to cycle calibration of Atlantic climatic records to Mediterranean sapropels and astronomical oscillations. *Geology*, **28**, 695-698.

SIGNOR, P.W. III & LIPPS, J.H. 1982. Sampling bias, gradual extinction patterns and catastrophes in the fossil record. In: SILVER, L.T. & SCHULTZ, P.H. (eds) *Geological implications of the impacts of large asteroids and comets on the Earth*. Geological Society of America Special Papers, **190**, 291-296.

STONE, P. 1995. Geology of the Rhinns of Galloway district. *Memoir of the British Geological Survey*, Sheets 1 and 3 (Scotland).

TAYLOR, L., ZALASIEWICZ, J.A., RUSHTON, A.W.A., LOYDELL, D.K. & RICKARDS, R.B. In preparation. Graptolites in British stratigraphy. *Special Report of the Geological Society of London*.

THORNTON, S.E. 1984. Basin model for hemipelagic sedimentation in a tectonically active continental margin: Santa Barbara Basin, California Continental Borderland. In (Stow, D.A.V. & Piper, D.J.W.; eds) *Fine-Grained Sediments: Deep-Water Processes and Facies*. Geological Society, London, Special Publication, **15**, 377-394.

UNDERWOOD, C.J., CROWLEY, S.F., MARSHALL, J.D. & BRENCHLEY, P.J. 1997. High-resolution carbon isotope stratigraphy of the basal Silurian Stratotype (Dob's Linn, Scotland) and its global correlation. *Journal of the Geological Society, London*, **154**, 709-718.

WEBBY, B.D., COOPER, R.A., BERGSTRÖM, S.M. & PARIS, F. 2004. Stratigraphic framework and time slices. In (Webby, B.D., Droser, M., Paris, F. & Percival, I., eds) *The Great Ordovician Biodiversification Event*, pp. 41-47, New York: Columbia University Press.

WILLIAMS, S.H. 1982. Upper Ordovician graptolites from the top Lower Hartfell Formation (*D. clingani* and *P. linearis* zones) near Moffat, southern Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **72**, 229-255.

WILLIAMS, S.H. 1994. Revision and definition of the *C. wilsoni* graptolite Zone (Middle Ordovician) of southern Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **85**, 143-157.

ZALASIEWICZ, J.A., RUSHTON, A.W.A. & OWEN, A.W. 1995. Late Caradoc graptolitic faunal gradients across the Iapetus Ocean. *Geological Magazine*, **132**, 611-617.

ZALASIEWICZ, J.A., RUSHTON, A.W.A., HUTT, J.E. & HOWE, M.P.A. (Editors) 2000. *Atlas of Graptolite Type Specimens*. Folio 1. Paleontographical Society. (And 42 single-authored, 13 co-authored contributions therein).

ZALASIEWICZ, J.A. 2001. Graptolites as constraints on models of sedimentation across Iapetus: a review. *Proceedings of the Geologists' Association*, **112**, 237-251.