Ballantrae Ophiolite as a *separatively emplaced*~~n~~ HEO in the frame of the

Grampian I, II and Caledonian tectonic sequence in the British Isles, 590 - 390 Ma, with Silurian crunch, post-subduction magmatism and Pridolian re-splitting

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Abstract

On the basis of the hot-emplaced ophiolite (HEO) model of *Osmaston (1979, 1980, 1995a, 2001a*) for the genesis and emplacement of such ophiolites, the Ballantrae Ophiolite marks the initiation of a new MOR near the Iapetus margin and subduction is not involved. Further, the HEO model involves the induced diapiric splitting of a sufficiently thick tectonic plate, not the stretching customarily assumed in the circumstances of early separation. The paper is presented as a test case for this controversial feature of the model. We show that these features further the understanding of observations at several junctures in the overall sequence of events, enabling these to be synthesized in a complicated but exceptionally coherent and precise manner of time and space throughout the last half of the 590-390Ma interval at issue, and rather less precisely for the preceding 100Ma. The geologic timescale of *Gradstein et al (2004*) is adopted throughout. Tectonics, sedimentation, palaeontology and magmatism are all intimately involved, as are repeated examples of basal subduction tectonic erosion (STE) and post-subduction magmatism (PSM), processes whose characteristics are summarized by way of introduction. This understanding of the subduction process, freed of the need to be able to emplace HEOs, enables precise interpretation of the observed structures. The analysis is assisted throughout by the recognition (outlined in an Appendix) of a sensitive new mechanism of thermal epeirogenic behaviour which distinguishes crustal blocks of differing character.

A primary Grampian tectonic sequence ('Grampian I') appears, by application of insights from the author's studies of constructing the Alps, to have been the result of a NW-directed closure during the 590-540Ma interval, of a 'proto-Grampian ocean', far to the southeast or ESE. This STE-undercut the northwestern plate extensively, culminating in a steep subduction interface downbend, now marked approximately by the Geal Charn-Ossian-Loch Awe Syncline-Leannan Fault line of structural divergence. Construction, including nappe formation, took place beneath this extensive Austroalpine-equivalent roof belonging to the northwestern plate. The proto-Tay Nappe, with a cover of Argyll and Southern Highland Group Dalradian, was a partially subducted imbric of that STE-undercut margin. Inversion of its cover occurred when final closure of the opposing ocean margin imported a block of ancient crust beneath it, subsequently exhuming through that roof as the Central Highlands tectonic window. Elsewhere, 630-600Ma ages typify the basement imported in this manner (Novantia, Cockburnland, Midland Valley, Tyrone, Ox Mountains, etc.).

Grampian I was followed by plate-splitting events at two main sites. The first (A), creating the line that is now the Highland Border-Clew Bay (HBCB) Line, marked by the Bute HEO at ~537Ma, involved (at least) the detachment of Connemara and a small strip on which the Leny Limestone was then deposited. This may actually have been the first of two motions in differing directions, the second being marked by the StAnthony and Thetford Mines HEOs in Canada. From that moment, the term 'Grampian Orogeny' does not describe what went on in Connemara. Closure of the resulting oceanic strip, by SE-ward subduction, began at ~490Ma, switching by ~475Ma to NW-ward at the HBCB Line, leading to the Grampian II event, closure being complete ~448Ma, and was the counterpart of Taconian closure in the Appalachians.

The second site (B) was further S, and within the already-existing Iapetus Ocean, being at some distance (= width of the later-imbricated proto-Southern Uplands Northern Belt (NB) Basin) to the S of the continental shelf of Cockburnland (CBL) (strictly *sensu Walton 1963*). CBL is a now-buried southern extension of the Midland Valley terrane, forming the northwestern passive margin of what was left of the main Vendian(?) Iapetus Ocean. Initiation of Split B at ~483Ma (late Tremadoc) produced the Ballantrae Ophiolite (BO) and emplaced it NW-ward across the proto-NB basin onto the CBL shelf. Further west, the same split passed along the south side of a metamorphic terrane (Novantia), a former part of CBL, here bounding the outside of the proto-NB basin. The Tyrone Ophiolite, emerging from this split, was emplaced direct onto this terrane, detaching a slice now seen as the Central Inlier of Tyrone, before (like BO) passing over the basin behind. Two mechanisms of thermal epeirogenic uplift (see Appendix) were, in turn, responsible for this sliding.

At the SE margin of Iapetus, early Arenig to mid-Llanvirn subduction STE-undercut, by >400km, the Manx-Welsh and Irish sectors but not the Lake District/English one. This was halted by the arrival of intra-Iapetus terranes and major PSM (Borrowdale, English Midlands, Snowdonia, Leinster) ensued in Caradoc (note that base Caradoc=base *gracilis* biozone=461Ma), after an intra-Llandeilo hiatus. Meanwhile, at the NW side of Iapetus, this cessation of subduction accelerated (but did not complete) closure of the Highland Border, now by NW-directed subduction, eventually causing the Highland Border Downbend of the inverted Tay Nappe. This event caused faulting, conglomerates (Kirkland, Benan, Kilranny, Corsewall) and intraplate volcanism at the CBL margin and in the NB basin to its south. In early Caradoc it also strike-slipped, sinistrally, the ancient arc terrane, Novantia, into position close to the southern edge of the NB basin, but within early Arenig crust that had emanated from the BO-initiated MOR, whose axis was now far to the south. Highland Border closure produced Grampian II deformation in the north and (mid-Caradoc) made subduction jump to the south of Novantia where, after brief arc development on Novantia, it proceeded rapidly to STE-undercut it, the NB basin behind it and that part of the CBL shelf upon which Ballantrae Ophiolite was resting, arriving there in early Llandovery and setting up a volcanic arc NW of Ballantrae.

Starting in latest Mid-Llandovery - earliest Late Llandovery (late *sedgwickii* biozone to basal *turriculatus* biozone (now called *guerichi*) = 437-436Ma) the accretionary front of this subduction zone slightly diachronously encountered Iapetus' thickly sedimented southeastern continental rise (Ettrickbridge tract in Scotland). Temporary hold-up at the foot of the SE shelf, but with underlying NW-ward subduction continuing, resulted in progressive SE-vergent imbrication and uprighting (partly in tiered duplexes) of the entire undercut NW margin (whose emergence sourced the Hawick rocks),

reaching the BO-Girvan area in early Wenlock (428Ma), when plate closure was briefly transferred to the WNW-directed Moine and Outer Isles thrusts, with a sinistral component along the Great Glen Fault. A moment later (early *riccartonensis* - 427.5Ma?) the SU accretionary front succeeded in surmounting the edge of the English sector shelf (former Ordovician forearc) and the SU Southern Belt was then accreted, finally halting nearer the Lake District in late Wenlock (late *lundgreni*=423.5Ma). On this interpretation most of the SU is not in fact of accretionary character, this being confined to the Southern Belt and the youngest parts of the Central Belt, all the rest being a quite late imbrication and up-edging of the STE-thinned NW margin, completed when it reached the BO complex in early Wenlock.

Reactivation of the old SSE-dipping subduction interface under northern England then offered further plate closure options by reversal of vergence and, starting almost immediately (423Ma), the now-imbricated and up-edged SU-Ballantrae assemblage, including Longford-Down (LD), was further back-thrust onto CBL passing over its Late Llandovery arc, completing this at 419Ma (early Pridoli). The agent for this was NNW-directed overthrusting by the SE margin, seen in the deformation of LD, and at Pomeroy and Ballantrae.

The previous shelf-encounter events (437-428Ma) had slowed and eventually halted (423.5Ma) the NW-ward subduction, giving time for reheat (from its LVZ) of the relatively young slab, the product of the MOR initiated by the Ballantrae HEO event. So PSM set in, starting in NW Highlands at ~428Ma and migrating S-ward (a diagnostic of PSM) to 397Ma (Criffel Granite) through the now-backthrust Southern Uplands (SU).

In the Manx-Welsh and Irish sectors of the SE border of Iapetus, the previously-extensive STE-undercutting of them completely transformed the resulting crunch tectonics. In the Manx-Welsh sector there was progressive SE-vergent imbricate thrusting of the thinned margin (NW Manx, Carmel Head, Tremadoc(?), Tywi), initiation of these being multiply constrained by tectonics and turbidite stratigraphy to early *turriculatus (guerichi)* (436Ma), but continuing till well into Wenlock. In the Irish sector also, the Longford-Armagh part of the SU's continuation pushed and deformed the southern margin on meeting it, acquiring younger sediments from that (the Aughty and Bernagh-Arra inliers belonged to the Central Belt) eventually being overridden by that margin and progressively overturned to the NW. This implied a reversal of subduction vergence ~427.5Ma, some 4Ma earlier than in the English sector, requiring the relict Iapetus Ocean plate to undergo a transform motion for that period. *Lundgreni*-age subduction-type volcanics in Dingle and the 423Ma Carnsore Point Granite illustrate the resulting reactivated subduction magmatism (RSM). In both sectors, huge amounts of shell-bearing sediment came at this time from the thrust-uplifted SE shelf, furnishing the deposition in Ireland (Sl. Bloom, Sl. Phelim-Silvermines-Devilsbit, Balbriggan), the Isle of Man (Niarbyl Fm) and in Denbigh, N Wales.

Finally, closure having now reached its limit, slab pull had been developed by this reactivation of the Ordovician SE subduction zone. This became operative when (418Ma? - early Pridoli) brief re-splitting of Avalonia-Laurentia resulted in ~25km SSW-wards separation of Avalonia, forming the Lower Tweed Basin and Solway Firth, passing into central Ireland to the south of the former Longford-Down complex and triggering the split of the Aughty-Bernagh inliers SW-wards from it, all beneath the overlying thrust-sheet. Slab pull then dragged the inliers up to 132km further to SW beneath the ex-shelf, while their roof sheet rode up towards the Silvermines-Devilsbit area. An epeirogenically positive crustal block, inferred to underlie the Burren uplift, S of Galway Bay, participated in this motion. Basement xenoliths in Carboniferous volcanics in the basin areas thus generated were derived from that of the heavily eroded former shelf that had overthrust all this activity but then subsided on the newly created floor around the blocks. The geometrical precision (± 2^{O} and locally ± 2km?) and kinematic coordination with which this sequence of four separations can be map-outline-delineated and reconstructed shows that plate separation was by well-defined splitting, not by stretching, so supports this aspect of the HEO model.

Two of these Irish Midlands motions interrelated with two linear separations of Charlestown from S Mayo but with 62 ± 1^{O} CW rotation of Connemara from the Strokestown lineament, causing major post-Ludlow relative deformation of the Murrisk region. Further east, and later, actual detachment of the subducting slab must have occurred, accelerating its descent and causing major shear-induced melting of its interface crust, sourcing genesis of the Leinster batholith (404Ma).

An Appendix outlines the action of two further processes called into play by the foregoing analysis. One is the generation of Intermediate Crust (IC) by the ‘clean’ splitting of tectonic plates in the presence of active sedimentation or other heat-retaining mechanism. The other is an efficient, newly identified thermal-petrological epeirogenic mechanism which acts differentially on crustal areas according to their deep crustal constitution, a distinguishing feature of IC relative to mature continental basement.

Overall, the activity of the MOR initiated by the Ballantrae (and Tyrone) ophiolites created ocean floor in the N part of Iapetus while older floor was subducted at the southern margin. This provides for the following:- (i) a narrow strip of early Arenig floor between Novantia and the uplifted S edge of the NB basin floor as a source of the puzzling Raven Gill imbrics intercalated between younger ones in the Leadhills Imbricate Zone of the SU; (ii) young enough ocean plate to subduct under Scotland until 423.5Ma to cause the 428-397Ma migration of PSM and provide heat for the '400Ma' Grampian regional uplift; (iii) southward migration and docking of the Llanvirnian Grangegeeth Terrane (eastern Ireland) bearing old Laurentian shelly fauna but which, in early Caradoc, acquired Avalonian ones that had not yet reached Laurentia; (iv) southward subduction of <25Ma-old post-Tremadoc ocean plate, S of that terrane, to enable the voluminous Caradocian PSM of Borrowdale-Snowdonia. In contrast, the standard subduction-based model for ophiolite emplacement implies subduction of the parental MOR, not the initiation of one that the above features require. Furthermore, the integration of the foregoing story strongly depends upon other HEOs in the Caledonian-Appalachian belt being interpreted similarly (Bute, Tyrone, StAnthony, Thetford Mines, Bay of Islands) with due regard to their ages.

Our analysis of the Caledonian crunch sequence in the British Isles shows that slab pull played a very limited part, confined to the very end and probably only in Ireland. Slab pull is an unsuitable agent for the development of flat subduction interfaces by STE action, an important player in both Grampian I and Caledonian sequences, and the late switch of closure to the Moine Thrust Zone requires that the Avalonia and Laurentia plates were being pushed together by external forces, not sucked together by slab pull beneath the SU. [2100 words**]**

1. Introduction

The primary aim of this document is to provide in outline a synthesis, in strict time, space and mechanical linkage, and with due attention to the magmatism, of the 'Caledonian' (as distinct from Grampian) sequence of events affecting the British Isles during the ~100Ma time interval - earliest Tremadoc to mid-Devonian 490Ma-390Ma, in the course of which it appears that an interpretation of the (nominally 481Ma) Ballantrae Ophiolite event as marking the initiation of a major addition to the Iapetus Ocean (rather than a moment of closure) impinges fruitfully at various junctures throughout that time. Timings are constrained to the maximum degree not only by precise palaeontological and radiometric measurements but by rigorous attention to dynamical constraints based on the order in which things must have happened. At the northern margin of Iapetus, however, this coverage interval is rendered dynamically too restrictive by arguments that at least the late stage of the Grampian orogeny occurred within it. So it has proved necessary first to work out how the principal structural dispositions that appear to have existed in the Grampian tract at the start of Cambrian time (542Ma) may have come about.

The secondary aim, therefore, is to show that the success of such an integrated synthesis requires the recognition of a variety of other changes in our perception of how the Earth works, notably its processes of horizontal separation and convergence and those of epeirogenic action, both upward and downward.

Although individually defined at first mention in the text, Table I is a list of all the abbreviation letterings adopted herein. Suitable illustrations for this outline, though not all prepared specifically for it, are listed in Table II, with some tentative captions. Stemming from an original proposal on ophiolite genesis by *Osmaston (1979, 1980)* it is written in the context of subsequent extended abstracts (*Osmaston 1995a, 2001a,* reinforced by *Osmaston 2001b*) and of their successor manuscript currently in gestation. The theme of these (collectively referred to hereinafter as '*Two Breeds*') is that there are two breeds of ophiolite, hot-emplaced (HEO) and cold-emplaced (CEO) but that the former, although (like all ophiolites) primarily generated by plate separation, are emplaced supracrustally in a diapiric manner, followed by epeirogenically-caused gravity sliding, *wholly without the aid of subduction*.

The essential feature of the HEO model is that the plate separation is not a stretching process but is a diapirically-supported vertical split extending far into the mantle and accreting laterally as the crack widens, as in the notably successful new MOR model of *Osmaston (2000a, 2006*). In this case, if the plate is thick enough, as is now seen generally to be the case elsewhere (*Osmaston 2006, 2007*), the tall column of emplaced hot mantle, laterally accreted layer by layer, can (if this is done quickly enough) build up an *integrated column buoyancy* sufficient before it is ~10km wide suddenly to break loose from its margins. This column buoyancy, impossible to build unless the split confines it laterally, then pushes its top part above crustal level, making it 'overflow' laterally in a laccolith-like form onto the adjacent basin floor as the quasi-solid mantle tectonite. In so doing, the tectonite may or may not, according to the vagaries of fortune, carry upon it some of the crustal section generated during the lateral accretion stage. Chemically this will be of MORB-like character. During this ‘burst-out’ diapiric rise of the tectonite, shear-induced segregation of residual interstitial melt occurs at depth, *via* the dilatancy mechanism. This melt freezes on the way up, typically as mafic granulite, due to lateral cooling by the older walls, and results in the mafic HP/HT part of the metamorphic 'sole', and sometimes in similar segregation bands within the tectonite. To rise from the pressure thus recorded (sometimes >40km; it is ~45km in the case of the Ballantrae Ophiolite (*Jelinek et al 1980; Treloar et al 1980; Smellie & Stone 1984*)) and be, in the existing 'obduction' model, pushed onto a margin would require a slope far more extensive than is conceivable, and a time longer than available, in view of the limitations on such slopes set by avoiding structural failure (probably no more than 1-2deg; *Forristall 1972*), especially in the case of such a hot body. The lower (main) part of the metamorphic sole, usually displaying a sedimentary protolith, results from its subsequent passage (gravity sliding) over the basin floor sediments. Supra-subduction-zone (SSZ)-like magmas are then produced simply by the water from those overridden sediments entering the hot tectonite and lowering its solidus (*Osmaston 1980*). Some production of SSZ-like magmatism is therefore an expectation of the HEO model and the genesis of trondhjemitic or plagiogranitic intrusion is seen as one of these, so their ages do not precisely mark that of HEO genesis, but are somewhat younger, depending on the size and cooling time of the tectonite 'laccolith'. Similarly, hornblende in the mafic sole is a product of transmitting this water, so it does not record the date of HEO origin either.

CEOs, on the other hand, are seen here, not as transferred ('obducted') from the downgoing plate, but as deriving from ocean-crusted forearcs by imbrication, enabling them readily to appear at the rear of accretionary prisms. Having thus originally been constructed at or close to a passive margin (before it became an active one), their construction process would often have been much affected by the presence of active clastic sedimentation, a situation absent at true MORs (see ***Appendix***). In their rôle as representatives of former ocean-crusted forearcs they are the predominant form in orogens such as the Alps (*Osmaston 1985, 1988, 1997, 2004* and *submitted*). This interpretation of CEOs as not having come from the downgoing plate is consistent with our recognition, developed in this paper, that subduction is prone to the removal of material from the upper plate, rather than adding to it other than superficial sediments.

In the HEO model two thermal-petrological-epeirogenic processes (*Osmaston 2001a*) are successively involved in the uplift, sliding and final emplacement. A failure to recognize these has been one of the reasons for continuance of the popular view that they have somehow been ‘pushed uphill”, a process whose severe structural limitations were noted above. They are (see also the ***Appendix*****)**:- (i) Heat from the adjacent split causes garnet-to-spinel peridotite phase change (up to 50 times more volume increase/joule than thermal expansion) in the mantle beneath the just-emplaced ophiolite and, after a conduction-time delay, uplifts it several kilometres, causing sliding (see my file *2ophFig9.pdf)**(FIG.5).*** (ii) Loading depression ahead of it enables it to slide onto the continental margin; this 'lid', whether hot or not, then causes an increase in deep crustal self-heating and the metamorphic release of water which cannot escape, which results in epeirogenic uplift (thermally >10 times more efficient than thermal expansion).

This paper repeats, updates and considerably extends the content of my 1986 London Geological Society-rejected 'Memoir' ms. on Caledonian closure in the British Isles *(Osmaston 1986),* adjusting it in the light of recent work, particularly the new geologic timescale (*Gradstein et al 2004a,b* - henceforward '*GTS2004*', but with stage-dates carried forward, where necessary, from *Gradstein & Ogg (1996)(GO’96)* and the paper (*Stone & Merriman, 2004* - henceforward '*SM04*') concerning the Northern Belt of the Southern Uplands. The revised correlations of the Silurian (*Cocks et al 1992*) and Ordovician (*Fortey et al 2000*) rocks of the British Isles have also tightened dates and removed mechanical contradictions in the interrelated timing of events. Except where otherwise cited all biostratigraphic ages used herein come either from these correlations or from the important contribution of *Floyd (2001 TRSE*) (Southern Uplands only). Another important contribution is that of *Woodcock et al (1999a) (GSL SP 160)* (Isle of Man). For the period at issue here the age uncertainty brackets in *GTS2004* range from ±1.5Ma to ±2.3Ma but only the central values (rounded to the nearest 0.5 Ma) will be employed here.

Timing is of the very essence of the story to be unfolded. To convey more directly, therefore, the sense of relative timings of events to those not habitually involved with the minutiae of Ordovician and Silurian graptolite biostratigraphy, we will revert, as convenient, to the former practice of designating (but with the *Rushton (2001 TRSE, Fig 3)* biozonal allocations) the Lower Llandovery (or Rhuddanian) graptolite biozones as A1-A4 (*acuminatus-atavus-acinaces-cyphus*), Mid-Llandovery (or Aeronian) as B1-B6 (*triangulatus-magnus-leptotheca-convolutus-sedgwickii-halli*) and Upper Llandovery (or Telychian) as C1-C6 (*guerichi/maximus-turriculatus-crispus-sartorius-griestoniensis- crenulata*). In this context the *sedgwickii-turriculatus* (B5-C2) interval emerges as a particularly busy one palaeogeographically. This may be why faunal change has made it possible to subdivide *turriculatus* (which formerly embraced *maximus*) even further, into at least 5 subdivisions (*Loydell 1992, 1993;*

Rushton 2001), but this refinement will not be applied here. Furthermore, the *crenulata* biozone at the top of the Llandovery has now been further divided but there is no point in making such distinction in this paper when citing papers that merely record '*crenulata'*. Suffice to note here that this time interval implied was apparently longer than most other biozones. This ~20-fold subdivision of the 15Ma duration of the Silurian (excluding Pridoli) illustrates the remarkable time resolution that it offers. For an earlier busy interval, that of *teretiusculus-gracilis,* the former is now (*GTS2004; Fortey et al 2000*) the sole occupant of the Llandeilo, which in turn constitutes the Late Llanvirn, reversing the decision of *Williams et al (1972)* to allocate the *gracilis* biozone to the Llandeilo, and the whole of *gracilis* now forms the lowest biozone of the Caradoc. This has major implications when scanning the literature, where very many older papers have assigned a 'Llandeilo' age when a *gracilis*-aged fauna was in fact the case. Hopefully, correction for this has been successful here.

The paper begins with outlines of the mechanism and characteristics of the two subduction processes that appear to have played a repeated and essential part in the story.

2. Post-subduction magmatism (PSM); its nature and predictable characteristics

The PSM idea, subsequently supported by study of many other examples, originated from my realization in 1984, in the context of *Watson (1984),* that the Siluro-Devonian granites and subduction-type volcanism in Scotland mostly post-date the firm date (late *lundgreni* biozone, see later) at which it is clear that the Southern Uplands (SU) had arrived in approximately its present close juxtaposition with the English Lake District. The implementation of that result can only follow if (contrary to the widely-held assumption) the subducting oceanic plate includes, below the notional 'slab' but mechanically integral with it, a thick layer of still-hot LVZ (seismological low-velocity zone) material (*Osmaston 2006*). [Note that LVZ interstitial melt of under 3% removes the water-weakening of the mineral structure, increasing its rheological resistance by up to two orders of magnitude (*Hirth & Kohlstedt 1996*), and markedly lowers its thermal conductivity (*Snyder et al 1994; 1995; 1996)*.] In that case, so soon as the top of the subducting oceanic plate ceases being cooled by contact with the ocean and then by shallow rocks of the upper plate, pressure increase will restore the thermal conductivity of the LVZ and reheating of the 'slab' component of the subducting plate will commence, mainly from below.

If this idea is correct the first evidence of that reheating will be a fading-out of the seismotomographic signature of the cold-slab component. Then, if the time and heat available for reheating is sufficient (e.g. if subduction ceases and the subducted plate is not too old), it will partially melt the oceanic crustal material lining the subduction interface. Because, if that happens, the entire thickness of the subducted crust is available to source this magmatism, PSM would be expected to be characterized by large magmatic volumes and at any particular point on the interface (in the case of ceased subduction), to be drawn out over a considerable interval of time as the heat reaches it. Other aspects that follow from the large import of heat to crustal levels by PSM's large magmatic volumes and of their wide areal spread are the possibilities for crustal anatexis and regional uplift and metamorphism; these can be expected to be especially significant where the source area is at a great depth on the interface, because the solidus, which determines the temperature of the released melt, is higher there in relation to an adiabat.

All of these effects are widely seen; the '400Ma' regional uplift in the Scottish Grampians (*Dewey and Pankhurst 1970; Dempster 1985*) being an apparent example of the latter, although the tomographic fade-out of slab signatures (see *Fukao et al 2001, Rev Geoph* for examples) has often been attributed to hypothetical 'slab drop-off**'.** Not only is slab drop-off thought have no general bearing upon the observation of arc-type and silicic magmatic materials (granites, andesites, rhyolites, etc) but PSM also predicts, in accord with observation, that the <u>onset</u> of such magmatism should commence above the deeper part of the subduction interface and migrate to above the shallower part because the deeper part has had more reheat time (while it was getting there).

Note that, once started at a particular point upon the subduction interface, the melting will continue until the crustal resource has been exhausted; so in documenting the migration of PSM it is the dates of onset that must be sought, though the volume-rate of melt material may increase for a time at that site. A further point is that the progressive crustal heating associated with continued input of interface-derived magma at any particular place may alter the degree of anatexis and therefore the chemistry of the granite produced. In the guise of ‘post-collision magmatism’ this kind of magmatism has been widely recognized, but not its systematic migration behaviour (‘sweep-back’) that is diagnostic of its nature (*Osmaston 1992a*). Now that zircon dating has the precision to plot the <40Ma age range that may be involved, such sweep-back is to be seen in late Archaean greenstone belts (*Corfu and Davis 1992 (Geology of Ontario); F.Corfu pers comm 1995*), where the source of the large heat input implied by the big TTG volumes intruded quasi-coevally across wide belts has hitherto been a puzzle. The apparent prevalence of ‘flat’ subduction (see Sect 3) and the much thicker oceanic crust (source volume) at that time explain both the wide extents and the very large volumes too *(Osmaston 2001c, GSA).* Among Phanerozoic examples, that which followed the Laramide orogeny in western USA (*Coney & Reynolds 1977*) proves that (as, presumably, in most of the Archaean also) the relevant factor is not continental collision but the cessation of subduction. Obviously, the availability of enough heat for PSM, particularly if it is to cause regional metamorphism, will depend to some extent upon the subducted plate being fairly young. This youth is a well-established fact for the Laramide case just mentioned *(Atwater 1989)* and it will be shown later that the ocean plate being subducted NW-ward during the final stages of Iapetus closure in the British Isles was indeed young too - much younger than the 'old' part of Iapetus previously subducted southward - the MOR from which the former emanated having been initiated by the Ballantrae HEO event. My Rio de Janeiro IGC abstract (*Osmaston 2000a*) and *Osmaston (2006*) have outlined a new continuous-process MOR model that generates ocean plate with the right attributes and in accord with MOR observations. The HEO model is a special case of that model, concerned with how that process starts, under the different conditions then prevailing.

It should be explained that the term 'sweep-back' (first used by *Coney & Reynolds 1977*) does not here refer to its geographical starting point relative to the former syn-subduction magmatism (SSM) arc but merely to its trenchward direction of migration. In the case that the active subduction interface had been normal (i.e. unmodified by STE - see below), with a typical dip of 25-30deg and with arc magmagenesis from a point at say 100km depth on the dipping interface, the onset of PSM will be from a much deeper point (350km?) on the interface and will work its way back across strike (for as much as 500km in this case), perhaps to no further than the original sub-arc point (too cool beyond that). On the other hand, where, as in the two 'flat-subduction' sectors of the Andes, the downbend beyond the gently-dipping 'flat' zone is now at more than 100km depth, it is clear that, if subduction were to cease, PSM initiation might also migrate for a long way back along the shallow-dipping part of the interface. In either case this behaviour creates a wide-area distribution of magmatism quite unlike the linearity of arc volcanism. These points bear significantly upon our interpretations of Ordovician and Siluro-Devonian PSM given below.

Slab ‘roll-back’ has widely been invoked to explain trenchward/oceanward migration of magmatism also. The underlying assumption for that is the presence of slab-pull but this assumption is inappropriate for reasons. (i) The observed fading of slab tomographic signatures at mid-Upper Mantle depths *(Fukao et al 2001; E.R. Engdahl pers comm 2001)* means that slab pull is minimal, regardless of whether the slab has reheated or 'dropped off'. Most of the geophysically computed slab pull has derived from that part of the slab assumed to go beyond 400km depth (*e.g. Minear & Toksoz 1970*). (ii) The widespread occurrence of the other subduction process, STE (see below), can only be achieved if the subducting plate has enough buoyancy to maintain quasi-horizontal contact with the upper plate over long distances. Plate buoyancy cannot suddenly be lost. (iii) The development of flat subduction profiles by STE is associated with widespread and progressive foreland-directed thrusting in the upper plate (*Molnar & Atwater 1978; Jordan et al 1983*). Note that (see ***FIG.1***, filename *stebasi2.pdf* and *Osmaston 1995b*) the age of the subducting plate is <70Ma for both the Andean flat-slab segments in which STE is currently very active. In the flat-slab run-up to the western USA Laramide events, mentioned above, the slab was very much younger than that (*Atwater 1989)*.

There is one situation, however, in which slab pull appears to be a real mechanism and to which we will need to appeal in this paper. If extensive STE (see below) that had developed an extensive flat subduction interface shallowly beneath a margin has been halted by a prolonged cessation of subduction, the young oceanic plate left at shallow depth beneath the flatly undercut region will be able to continue its cooling, losing its buoyancy, and the margin will subside. If, now, collisional closure should reactivate the former subduction interface, pushing the now-cool ex-oceanic plate past the downbend curve carved by STE into the hanging wall will cause it to transform to dense HP mineralogy and develop substantial slab pull. This, we suggest, is what appears to have been going on in the Tyrrhenian Sea, creating young openings in its floor *(Osmaston 2007),* and a case will be made that it also happened in central Ireland in the latest Silurian. Just as the slab pull concept has justified people to ignore the mechanical guidance function of the upper plate so, it appears, in this case also, the sinking slab may do so more steeply and in directions independent of guidance by any prior subduction interface profile at the base of the upper plate.

Fortunately, there is another, and apparently more appropriate, mechanism for the particular phenomenon which originally gave rise to the term 'slab-pull' and has seemed most strongly to support the 'roll-back' idea in other circumstances, namely the bowing of arcs by the formation of back-arc basins. This is the *anticlastic curvature* mechanism, see *Osmaston (2006)* and ***FIG.2*** (filename *anticur4.pdf)***.*** The thicker plates are, as recognized by *Osmaston (2006*), the more powerful this mechanism. That it will operate in the presence of ridge-push resolves the paradox, to which attention was originally drawn (*Molnar and Atwater 1978*; *Uyeda and Kanamori 1979*), that subduction can, in different circumstances, evidently produce *either* back-arc opening *or* foreland-directed thrusting. The younger and thinner plates being subducted in the eastern Pacific only produce the latter.

Finally, for the slab-reheating interpretation of the tomographic fading of slab signatures in the intermediate depth-range to be valid, rather than slab drop-off, the ubiquitous return of a slab-like high velocity signature, starting again at ~400km and often going on into the lower mantle *(Fukao et al 2001*) cannot be due to temperature but must have a mineralogical cause that also explains the high energy release typical of deep earthquakes. The possibility of meeting these requirements was outlined by *Osmaston (2000b; 2003a; 2005c).*

Two further kinds of 'post-subduction' magmatism can occur, as a subduction-related inheritance, but maybe very much longer after the original subduction had ceased than in the case of PSM, as defined above. One, see Section 9.2.2.5, is what we will call reactivated subduction magmatism (RSM), evidently able to occur when an old subduction interface is tectonically reactivated and shear heating, amplified by the jerky nature of subduction motion, occurs at the former interface. The other, also dependent upon crustal material continuing for a long time to outline a former subduction interface deep into the mantle, relates to the possible origin of A-type granites (Section 12).

3. STE (basal Subduction Tectonic Erosion)

3.1. STE and syn-subduction magmatism (SSM)

The basic features of STE were outlined by *Osmaston (1992b)* and are illustrated in ***FIG.3*** (filename *downben3.pdf*) and ***FIG.1*** *(*filename *stebasi2.pdf).* In essence, STE is the mechanism by which so-called 'flat-slab' subduction develops. The popular geophysical view has been that such development is attributable solely to properties of the subducting plate but in a comprehensive study of 164 subduction zone transects *Cruciani et al (2005*) found no correlation between slab dip and lithosphere age. The popular view, moreover, has had little or no regard to what was going on, geologically recorded, in the upper plate. In fact, that record can be tied intimately to the progressive development of the interface profile. In the STE result, the shape of a flat interface profile is a record of what STE has done to the hanging wall/upper plate. Even where STE has progressed far enough to reach mantle depths, the upper plate is seen to have preserved a degree of mechanical solidity, capable of transmitting thrust failures from interface to the surface *(Gutscher et al 2000)* and preserving the interface profile thus carved into it for long periods (>30Ma?) while subduction continues. On a world scene and backward through time STE is to be seen, we suggest, as the only adequate mechanism by which extensive thrust sheets of metamorphic basement, deprived of their lower crust and underlying