Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Tectonic mode switches and the nature of orogenesis

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ARTICLE INFO

Article history:

Received 28 May 2008

Accepted 31 October 2008

Available online xxxx

Keywords:

Orogeny

Metamorphism

UHP

Precambrian

Alpine

Tectonic mode switches

Subduction zone dynamics

ABSTRACT

The birth and death of many mountain belts occurs in lithosphere that over-rides major subduction zones. Here the tectonic mode (shortening *versus* extension) can abruptly switch, even during continuous and otherwise smooth convergence. If the hinge line of the foundering slab rapidly retreats (i.e. rolls back), the foundering slab creates a gravitational potential well into which the orogen collapses. This motion, coupled with stress guides, can “pull” the orogen apart. A slowing of roll-back (or of hinge retreat) means that the subduction flexure may subsequently begin to be “pushed back” or be “pushed over” by the advancing orogen. The consequence of such changes in relative motion is that orogenic belts are affected by abrupt tectonic mode switches. The change from “push” to “pull” leads to a sudden change from horizontal extension to horizontal shortening, potentially throughout the entire mass of the orogenic lithosphere that over-rides the subducting slab. The sequencing of these tectonic mode switches affects the thermal evolution of the orogen, and thus fundamentally determines the nature of orogenesis. This insight led to us to our quite different views as to how orogens work. It is evident that orogens affected by abrupt “push-pull” mode switches are characterized by high-pressure metamorphism, whereas orogens affected by abrupt “pull-push” mode switches are characterized by high-temperature metamorphism, magmatism and anatexis.

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1. Introduction

Most orogens form adjacent to major subduction zones, and in some sense they act as plate tectonic “bumper bars”. In principle this simple (and widely accepted notion) would seem to imply that stretching or shortening of the entire lithosphere should accompany orogenic episodes. If this occurs, large strains can accumulate within the orogen during individual episodes. Both crust and its underlying mantle lithosphere will be deformed. Motion can be accommodated by a range of geometries ranging from terrane-stacks (Fig. 1a and b) to more homogeneous distributions of strain and displacement (Fig. 1c and d). During a “pull-push” orogenic cycle horizontal lithospheric stretching would be followed by subsequent lithospheric shortening, while during a “push-pull” orogenic cycle, horizontal lithospheric shortening would be followed by subsequent lithospheric stretching.

In this context we can describe what happens during orogenesis in terms of a number of reference velocities. Overall shortening will take place in the over-riding plate above a major subduction zone when the subduction hinge is “pushed back” or “pushed over” by the advancing orogenic front [i.e. with $v_4 \leq v_3 < v_2$] (Fig. 1a and c). In this context [v_2] is

the velocity of an advancing reference craton, and it exceeds [v_3], or the velocity with which the subduction hinge is retreating. The velocity of the advancing orogenic front [v_4] may remain the same as the velocity with which the subduction hinge is retreating [v_3], in which case the dynamics may be described as “push-back” (Fig. 1a). Should the velocity of the advancing orogenic front [v_4] exceed the velocity with which the subduction hinge is retreating [v_3], the result could be a “push over” the hinge of the advancing plate (Fig. 1c). The resultant geometry would be described as flat slab subduction, but this would have a quite different geodynamical significance than would a change in the relative buoyancy of the subducting slab itself, e.g. due to the arrival of a relatively buoyant oceanic plateau, or a continental fragment, at the subduction hinge. The effect of an indenter is nevertheless still explained by variation of relative velocities as identified above, but now, for example with [$v_1 \approx v_4 \approx v_3 < v_2$]. In contrast, lithosphere-scale extension can take place when the subduction hinge “pulls away” (or rolls back) of its own accord [so $v_3 > v_2$], where again [v_2] is the velocity of the advancing reference craton and [v_3] is the velocity with which the subduction hinge is retreating (Fig. 1b).

It should be evident, from the above, that the velocity of the subducting slab [v_1] itself does not directly enter into the equation, although through other geodynamic factors (e.g. stress coupling, flexural rigidity, buoyancy etc) this velocity will influence the motions involved above. The velocities noted above are nevertheless not the “drivers” that cause the great differences in the nature of orogeny that result from imbalances as noted above. Their relative values are important, for they

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Fig. 1. Velocities that determine tectonic mode switches: v_1 the velocity of the subducting plate, v_2 the velocity of the over-riding plate, v_3 the roll-back velocity of the subduction hinge, and v_4 the velocity of the orogenic interface. In: (a) terrane-stacking in the over-riding plate above a major subduction zone takes place because the subduction hinge is “pushed back” [$v_3 = v_4 < v_2$]; (b) lithosphere-scale extension and distension of the terrane-stack when the subduction hinge “pulls back” (or rolls back) [$v_3 = v_4 > v_2$]; (c) the orogen has been pushed over the hinge of an adjacent subducting slab, producing a geometry referred to as flat slab subduction [$v_4 < v_3 < v_2$]. The orogen is in overall compression; (d) the orogen collapses over the adjacent slab [here with $v_4 > v_3 < v_2$]. In (c) and (d) a large segment of the orogen is in either compression (c) or extension (d) above what must be a weak basal thrust. Note that the velocity of the subducting slab (v_1) does not directly determine tectonic mode.

offer a frame of reference that allows some comprehension of the underlying geodynamics, in particular in respect to geometry and the 3D-time evolution of the orogen.

2. Terrane-stacks and tectonic shuffle zones

Lithosphere-scale dislocations (i.e., brittle and/or ductile faults or shear zones) developed in the over-riding orogen will focus movement and lead to the formation of terrane-stacks (Fig. 1a). The notion of a terrane-stack is central to the interpretations presented in this paper, but the term is used in a deliberately imprecise fashion to allow that a range of different possible interpretations be taken into account. In principle a terrane-stack may be defined as the juxtaposition of different geological terranes as the result of deep-rooted thrusts. These thrusts may slice the geological entity in many different ways – hence the imprecision implicit in the terminology. A terrane-stack might be simply accomplished as illustrated in Fig. 1a, with no

differentiation of crust and mantle, and several lithospheric slices stacked one upon the other. Alternatively, and the more likely, as is the case with many major thrust systems involving large displacements, the architecture might become considerably more complex. Thrusting can involve initially thin-skinned décollement followed by more deeply rooted thrusts, and thereafter thrusts that bite through and/or transect an already complex geometry. It is immaterial whether these thrusts be considered “in sequence” or “out of sequence”. The terrane-stacks that result will be considerably more complex than the simple sketches provided for illustrative purposes in this paper.

Tectonic mode switches as described above lead to the effects of areally extensive thrusts being superimposed upon the effects of areally extensive extensional detachments, and vice versa. The movement zones that result thus display the effects of large horizontal components of motion in one direction, followed by the effects of large horizontal components of motion in the opposite sense (Fig. 2). We call the structures that result “tectonic shuffle zones” since their thinly-sliced tectonometamorphic stratigraphy, and the juxtaposition of seemingly exotic lenses, reflect the imprint of large, but opposing, sequential motions. Tectonic shuffle zones arise because extensional detachments formed after a thrust event, do not precisely follow the trajectory of the older thrusts, or vice versa. Fig. 2 shows how shuffling caused by reversal of opposing sequential movements on these structures is able to cause thin relict lenses of high-pressure rock to be stranded between adjacent tectonic slices, with each slice reflecting different P–T histories.

Tectonic shuffle zones will develop at terrane boundaries as the result of the opposing movements implied in the models illustrated in Fig. 1. This is of interest because tectonic shuffle zones seem to be aspects common to the structural geology of many orogens, at scales varying from that appropriate to describe a local tectonometamorphic stratigraphy, to scales appropriate to describe the stacking of lithosphere-scale tectonic slices. Thus we are able to explain the thinly-sliced tectonometamorphic stratigraphy that is a feature common to all known coherent high-pressure and ultra-high-pressure terranes. High-pressure tectonic mélanges may also be associated with such structures (e.g., in tectonic environments as described by Shervais et al., 2004).

3. Push versus pull in orogenic belts

It does not seem remarkable to suggest that shortening of the entire lithosphere takes place during orogenesis. It is more controversial to suggest that this can be accomplished by terrane-stacking, and that in consequence we need to revise our models as to the genesis of high-pressure metamorphic rocks. It is also apparently controversial to suggest that several cycles of lithosphere-scale shortening followed by stretching might take place during the evolution of an orogen. Conventional wisdom reduces orogenesis to merely two stages: a period of construction followed by a period of collapse. This contribution considers these issues and establishes the geometric basis of a different paradigm as to the nature of orogenesis.

In the modern Earth it can be argued that “push-back” against adjacent subduction hinges currently thickens the Andean lithosphere and simultaneously moves the trenches steadily closer to the spreading ridges from which the descending plate originated. In contrast, in Myanmar and southward into the Andaman Sea, in the western part of Indonesia, subduction hinges in the Indian plate are apparently “pulling away” from the adjacent orogen. This movement is taking place in directions roughly orthogonal to the adjacent arcs (irrespective of the direction of relative plate motion), stretching the over-riding crust (and lithosphere) and producing structural trends at various degrees of obliquity to the direction of relative plate motion.

There are thus two types of orogenic systems that can be distinguished on the basis of the behaviour of an adjacent subduction hinge. Compressional orogenesis occurs during periods when the over-riding lithosphere pushes against (or over) an adjacent subduction hinge. Periods of extensional tectonism usually have their origin in the

Fig. 2. Lithospheric dislocations developed in the over-riding orogen may focus movements, and lead to the formation of “tectonic shuffle zones”. The superimposition of a major thrust on a major extensional detachment fault leads to the thinly sliced geometry of a tectonic shuffle zone, with thinly sliced remnants of high pressure rocks from deeper levels in the crust stranded below an extensional shear zone or detachment. All that is required is the reversal of movement caused by a major thrust with the later formed detachment fault not exactly coinciding with the locus of the earlier formed thrust.

retreat (or “roll-back”) of an adjacent subduction hinge at rates faster than the over-riding orogen is able to advance (Royden, 1993; Lonergan and White, 1997; Royden and Husson, 2006). Fig. 1a illustrates a simple terrane-stack that may result from “push-back”. Fig. 1b shows how this lithosphere-scale terrane-stack can be distended as a result of later extension. Much follows from this simple diagram, in particular focussing our attention on the tectonic shuffle zones where such sequentially opposing movements must be concentrated.

We should not attach too much importance to the relative motion of the subduction hinge in terms of governing the stresses that operate within the orogen. We need also to consider that the orogen can be pushed (from behind) past the subduction hinge, so that the uppermost parts of the lithosphere slide over adjacent flat or gently dipping parts of the subducting slab. In this case the entire orogenic lithosphere is subject to horizontal shortening (Fig. 1c). Once we accept that such “push over” can take place, leading to what is commonly referred to as “flat slab subduction” (Ramos et al., 2002), we must introduce an additional semi-independent variable, namely the migration velocity of the orogenic interface, v_4 . Since the orogenic interface can move with a velocity [v_4] that is independent of the migration velocity of the subduction hinge [v_3], in some cases it is evident that $v_4 \neq v_3$. Note also that there are factors that independently govern a change in dip angle of the subducting plate, for example the arrival of a buoyant oceanic plateau (Gutscher et al., 2000). Although in this case the velocity of the orogenic interface [v_4] might be strongly influenced by the velocity of the subducting plate [v_1], and change to reflect the impact of this event, the transition to “flat slab subduction” is nevertheless governed by the same geometric principles as described above.

4. Gravitational collapse

In addition to “pull-back” and “push-back” of the orogen relative to the hinge of an adjacent subduction zone, the list of factors that affect

tectonic mode during orogenesis must also include collapse (Dewey, 1988). Once we accept that an orogen can collapse (driven by its gravitational potential energy) we must accept that the orogen can surge (manifested by foreland-directed thrusting) over the foreland itself (Fig. 1d). This means that tectonic mode is also determined by variation in the rate of collapse of overthickened crust within the orogen itself (cf England and Molnar, 2005). There must always be a basal thrust, but the width of the zone affected by shortening depends on how the collapsing orogen interfaces with the advancing under-thrust plate (in the case of oceanic lithosphere, e.g. in the Aleutian Arc) or with the advancing craton (in the case where the interaction takes place with continental lithosphere, e.g. in the Himalaya).

It is necessary to consider these additional factors if we want to provide a complete kinematic description of flat slab subduction, for example as described by Coney and Reynolds (1977), Jordan et al., 1983, Ramos et al., 2002, or to consider the geometry of the giant Sumatran megathrust which separates the westward flowing Indonesian crust from the gently dipping subducting Indian and Australian plates (e.g. Whittaker et al., 2007). The velocity of hinge advance or hinge roll-back needs to be considered separately from the velocity of the advancing or retreating orogenic interface. A slab cannot abruptly change its dip, but nevertheless the hinge can rapidly roll-back (cf Coney and Reynolds, 1977; Eaton, 1984). The orogen may collapse at the same time as hinge retreat takes place, and the orogenic interface can then advance over the retreating hinge onto the otherwise flat or gently-dipping part of the slab (e.g. as is the case in the Aegean, or in the Sumatran forearc). The opposite circumstances can also reassert themselves and renewed overall crustal shortening can once again lead to thickening crust being forcibly thrust on the flat slab (Fig. 1c), inverting earlier formed extensional structures. These are again circumstances in which the orogenic interface can move with a velocity [v_4] that is independent of the migration velocity of the subduction hinge [v_3], so again in some cases it is evident that $v_4 \neq v_3$.

Fig. 3. The geometry of extension in a schematic cross-section through the Sanak Basin in the Aleutian arc provides an example of how slab retreat can “pull” an orogen apart. As the Pacific plate founders, it creates a potential well into which the over-riding orogenic lithosphere has been drawn. In consequence the orogen has collapsed over the subduction hinge.

5. Do orogens collapse or are they pulled apart?

In passing we should note that slab retreat leads to “pull back” because flow of the orogenic lithosphere takes place to avoid the formation of a gravitational potential well. This flow is transformed into ‘extensional’ stresses by virtue of stress transfer into the stress guides in the adjacent over-riding plate. These stress guides are defined by the strong zones defined by the brittle-ductile transitions that are always to be found within the continental crust and mantle. These stress guides may be fractured and they then can fail, focussing motion on pre-existing structures that can be quite distal to the rolling back subduction zone that provides the driving force for horizontal extension.

In essence this coupling between flow induced by gravitational collapse and the buildup of effective tension in the stress guides present in any lithosphere allows slab retreat to “pull” an orogen apart. The consequent input of heat associated with the advection of hot fluids or magmas during extension further facilitates gravitational collapse of the orogen. The system is capable of exhibiting all of the elements of complexity theory, with non-linear feedbacks that govern non-linear response. Therefore, with respect to the question “Do orogens collapse or are they pulled apart?” the answer is that (mechanically and geodynamically) both options can be exercised, independently or in conjunction. Moreover, some of the contrasting effects of collapse and pull-apart can be distinguished in contemporary settings.

This point can be illustrated by considering a section through the Aleutian Arc (Fig. 3). The collapsing crust has over-ridden the Aleutian hinge. The gradual steepening of the over-ridden ‘flat’ zone of the foundering slab provides the motivating ‘force’ driving extension, generating a deepening gravitational potential well. Note that this is a rather different geodynamic scenario in comparison with the

Himalaya, where the topographic high that has been generated in the Tibetan Plateau drives flow of the collapsing Himalayan orogen southward over the advancing Indian craton (Royden and Burchfiel, 1987), eastward over the Sichuan Basin and northward over the Tarim Basin (Fig. 4 below). Nevertheless, in both cases the kinematics of the frontal wedge involves active extensional normal faults over-riding a basal thrust (Burchfiel and Royden, 1985; Burchfiel et al., 1992). Note also the propensity of such regions in generating great earthquakes!

6. The independent mobility of orogenic interfaces [v₄]

At this point we begin to discuss one particular orogen in some detail, making the transition between a conceptual introduction to a more rigorous analysis of movement in 3D-time, here for the Himalayan ranges. The real complexity evident in the evolution of any orogen begins to emerge once we begin to consider movement in this way.

The key observation that emerges from the preceding discussion is that the orogenic interface, whether it be trench or collapsing mountain front, is able to move with a velocity (and evolve into a geometry) that is to some measure independent of the velocities (and geometries) of the opposing plates. It is this relative mobility that determines tectonic mode. In the case of collapse, where tectonic mode is determined by differences in flow rates, small changes in relative motions may lead to tectonic mode switches. A wide zone of shortening in the marginal zone of a collapsing orogen may be the result of a transiently higher degree of coupling with the over-ridden foreland, slowing the movement of the orogenic interface. Collapse is hindered, so that the orogenic interface advances with the indenting plate and the zone of shortening widens, as is the case when an advancing indenter impacts on an orogen. The reverse occurs

Fig. 4. Geometry of a mountain front reflecting the impact of collapse driven by the gravitational potential energy of the orogen. Arrows show GPS motions relative to India (after Jade et al., 2004). The coloured slip lines stem from epicenters of 575 earthquakes in the period 1976–2006 in the depth range 0–60 km, as recorded in the Global Centroid Moment Tensor database (<http://www.globalcmt.org/>). Map produced using Program eQuakes (<http://rse.anu.edu.au/tectonics/equakes/>) superimposed on images derived from NOAA (<http://ibis.drdo.noaa.gov/cgi-bin/bathy/bathD.pl>). Each slip line shown represents a plausible choice of one of two conjugate fault plane – slip line solutions derived from the centroid moment tensor: each choice based on details of the local geology. Slip lines for thrusts (red), normal faults (blue), left-lateral strike-slip faults (green) and right lateral (yellow) are shown. Motion orthogonal to the mountain front is typical of the geometry of collapse where the orogen has spread over, or been pushed over the adjacent descending slab. Left-lateral Chaman fault zone (dashed) in the west (a). Right-lateral Sagaing fault zone (dashed) in the east (b).

if collapse is accelerated (e.g., by yield of the orogenic interface as a new thrust develops, and/or by weakening of warming crust in the hinterland). This leads to a surge that drives the orogenic interface over the indenting plate, developing characteristic arcuate geometries (cf Rosenbaum et al., 2002; Schellart et al., 2002; Schellart and Lister, 2004).

Motion orthogonal to an arcuate mountain front is typical of the geometry of collapse, where the orogen has spread over, or has been pushed over, the adjacent foreland. For example it can reasonably be inferred that the Tibetan crust collapsed southward to create the modern arcuate shape of the southern boundary of the Himalayan mountain chain (Fig. 4). In fact the mountain front defines an almost perfect small circle, with a radius of 1696 ± 55 km (Bendick and Bilham, 2001). GPS measurements suggest this flow is still occurring: present day movement is taking place in directions orthogonal to the modern arc (Jade et al., 2004) as illustrated in Fig. 4. England and Molnar (2005) provide a convincing argument that crustal flow in Tibet is driven by the gravitational potential energy of the collapsing orogen: in their words, the orogen behaves more like a ‘fluid’ than a ‘plate’.

This geometry is further illustrated in Fig. 4, using program *eQuakes* <<http://rse.anu.edu.au/tectonics/equakes/>> to help analyze the geometry of earthquakes for which motion has been determined with sufficient accuracy to allow calculation of the Centroid Moment Tensor (or CMT). For thirty years this CMT data has been collected by the Global CMT project <<http://www.globalcmt.org/>> and the results of their calculations made freely available to the scientific community. Program *eQuakes* uses data downloaded from this site, and overlays the data on NOAA images showing digital elevation, generated by Smith and Sandwell (1997) and Miller et al., <<http://ibis.grdl.noaa.gov/cgi-bin/bathy/bathD.pl>>. Data from individual earthquakes or from mapped groups of earthquakes can thereby be analyzed on a stereographic projection, and compared with whatever information is available as to the local geology. For example the program is able to use spherical trigonometry to draw a fault trace as it would appear if projected to the surface, based on the CMT orientation data and depth to the hypocentre. This allows comparison with topographic features, for example as evident on SRTM imagery, and a choice can be made of one of the two conjugate fault plane solutions that can be inferred from the Centroid Moment Tensor (CMT). Similarly the vector defining the slip line on individual fault planes provides additional constraint, for example in the case of kinematically coordinated faults where the fault plane solutions vary widely in their orientation but are nevertheless colinear (e.g., Lister et al., 2008).

In 80–90% of all cases examined, of the two fault plane solutions available, only one is entirely consistent with the local geology as inferred from this type of information. The result is a set of plausible fault planes, with corresponding slip line solutions. Individually these choices can be debated, and there is a need therefore to establish an internet presence to allow this to take place (e.g. showing a world slip map). The result that will emerge will be structural maps such as illustrated in Fig. 4, which shows colour-coded slip line traces portrayed on a Universal Transverse Mercator projection, itself superimposed on an image derived from <<http://ibis.grdl.noaa.gov/cgi-bin/bathy/bathD.pl>>. The coloured slip lines stem from epicenters of earthquakes recorded in the Global CMT database <<http://www.globalcmt.org/>> for the period 1976–2006, in the depth range 0–60 km. Slip lines for thrust faults are shown in red, slip lines for normal faults in blue, slip lines for left-lateral strike-slip faults in green, and slip lines for right lateral strike-slip faults in gold. Forward motion of the Indian indenter is accommodated in the west by the left-lateral Chaman fault zone (Wellman, 1966) on the boundary between Afghanistan and Pakistan, and in the east (in Myanmar or Burma) by the right-lateral Sagaing fault zone (Michel et al., 2000; cf Vigny et al., 2003).

This data can be used to make a number of critical observations. In the NW, this data suggests that the main focus of the India–Asia

collision is now in the NW, under the ranges of the Hindu Kush. Furthermore the impact of a currently active indenter can be inferred from the paired clusters of strike-slip faults (with right-lateral faults in the west leading to the Tadjik Basin, and dominantly left-lateral faults in the east, leading to the Tarim Basin). The Chaman Fault can be inferred to continue northward from its presently recognized extent south of the ~E–W Herat Fault, in Iran, and to link into the operation of the indenter. The many active thrusts over the Tarim Basin should also be noted, since these also demonstrate active convergence taking place in this zone.

In the south, this data shows active thrusts rimming the collapsing Tibetan Plateau, but only in the western part of the Himalayan ranges. We suggest that the small-circle geometry of the Himalayan mountain front is diagnostic of the fluid-like behaviour of this collapsing orogen. This geometry reflects the impact of radiating viscous flow, driven by the gravitational potential energy of the collapsing Tibetan Plateau. This inference is consistent with radiating GPS motions relative to India (indicated by the black arrows in Fig. 4, after Jade et al., 2004). The data also shows that thrusts radiate more or less orthogonally from the orogenic welt defined by the Tibetan plateau, southward, northward, and eastward. The effects of this eastward flow of the collapsing Tibetan Plateau is particularly evident in the fold and thrust belt in Sichuan Province, the locus of several catastrophic earthquakes (yellow dots in Fig. 4).

In contrast, in the east, this data shows that the tectonic mode in the Myanmar crust is determined by the competition between two nearly orthogonal movement patterns (Fig. 4). This is a movement pattern driven by the WSW-directed roll-back of the tearing Myanmar slab that lies beneath this zone. Shortening occurs in the foreland fold and thrust belt because this zone accommodates WSW directed motion of crust flowing out from the Myanmar hinterland. This material will eventually be over-ridden by the advancing Himalayan nappes. The Sagaing wrench fault zone marks the locus of accumulating right-lateral offsets, periodically accommodating distortions caused by relative plate motion. At the same time concentric left-lateral strike-slip faults accommodate flow around the eastern syntaxis, causing distortion of the Sagaing Fault and local transtension (Vigny et al., 2003). These concentric left-lateral strike-slip faults are most evident in Fig. 4, for the green lines that show the trend of fault plane slip vectors associated with left-lateral strike-slip earthquakes. From north to south, in a semicircle around the eastern syntaxis, the movement direction associated with these earthquakes changes from towards ~90° to towards ~250°. This same clockwise concentric pattern of rotation about the eastern syntaxis of the Himalayan ranges is also evident in GPS data (Michel et al., 2000).

7. The independent mobility of the slab hinge [v₃]

Tectonic mode switches driven by changes in the relative motion of the hinge of an adjacent subducting slab also depend on several competing factors. The hinge of an adjacent subducting slab can be pushed forward (over-riding its own descending slab), for example. This can be the result of a swerve in plate motion, as occurred during the Eocene motion of the Pacific plate. Locally this change in motion resulted in hinge advance, and caused folding and buckling of the descending slab (Schellart et al., 2006). This hinge advance was also responsible for the first period of obduction in New Caledonia. Alternatively the subduction hinge line may “pull back” (or “roll back”) of its own accord, so that the hinge line gets closer to the spreading centre from which the slab derived. Roll-back is often the result of a tear that develops in the subducting slab (Royden, 1993; Lonergan and White, 1997; Wortel and Spakman, 2000; cf Mantovani et al., 2001) since this allows the asthenosphere trapped behind the descending curtain defined by the subducting slab to escape laterally. Usually roll-back takes place at a rate that is initially faster than the over-riding lithosphere is able to advance, causing widespread extension.

8. Five semi-independent variables

The above sections demonstrated that four independent factors influence tectonic mode during orogenesis. Even small variations in the rates at which these competing processes take place may lead to tectonic mode switches that have pervasive influence throughout the orogen. Such mode switches can take place abruptly, even during steady and progressive convergence of two opposing plates, and as a result the orogen (on the scale of the lithosphere) may be abruptly switched from overall shortening to overall stretching, or *vice versa*. Variables that need to be taken into account are listed below:

- 1) the effect of an indenter – the velocity of the orogenic interface [v_4] and that of the subduction hinge [v_3] can be determined by the velocity of the subducting plate [v_1] when an indenting craton first begins to impact on an orogenic welt, or when roll-back has brought an oceanic plateau or a continental ribbon to the point that it must be subducted.
- 2) push-back by the orogen (e.g., against or over an adjacent subduction hinge) – in many cases the orogen is able to “push over” the foreland, or to collapse over and/or around an obstacle, in which case the velocity of the subducting plate [v_1] may have little influence on tectonic mode within the orogen. Tectonic mode will be determined by the rate at which the orogenic interface is able to advance [v_4].
- 3) pull-back (of the subduction hinge faster than the over-riding lithosphere is able to advance) – tectonic mode is determined by the rate of roll-back [v_3]. Roll-back is fastest when a subduction zone has been newly initiated (Schellart, 2004b) or when the descending curtain defined by the subducting slab has been recently torn, allowing flow of the asthenosphere through the gap, thence triggering roll-back. If a slab does not tear it will not roll-back.
- 4) collapse (driven by the gravitational potential energy of the orogen) during which the crust of the orogen flows (or conversely is forced) over the adjacent descending slab – collapse determines the velocity of the orogenic interface [v_4]. Three factors come into consideration namely: i) the rheology of the orogen – if it is weak it will flow; ii) coupling with the advancing foreland – a broad zone of strong coupling will determine a wide zone of shortening in the frontal region of a zone of collapse whereas a weak, newly broken basal megathrust will allow an individual surge of the orogen over the foreland.
- 5) accommodating (lithosphere-scale) strike-slip or wrench faults – since these partition deformation in individual compartments to motions that are more closely orthogonal to the boundaries of the orogenic welt.

Nowhere is the effect of these competing motions more evident than during flat-slab subduction (e.g. Jordan et al., 1983; Kay and Abbruzzi, 1996; Ramos et al., 2002). As indicated above, this geometry may equally result from: i) rapid collapse of the orogen over the adjacent slab; or ii)

forcing the crust (and lithosphere) of the adjacent orogen over a descending slab faster than this slab is able to founder. During collapse the crust may extend as it surges over the subducting slab, and the toe of the surge will still be marked by a zone of compressional tectonism. Alternatively, the entire crustal section may be subject to shortening as it is pushed over the adjacent slab (e.g. Ramos et al., 2002; Shervais et al., 2004). Since the motions are relative it matters not whether the underlying cause is increased buoyancy of the subducting slab as opposed to the effect of an increased rate of convergence as the result of more global influences. In both cases the orogen will either be pushed over the flat slab, or it will collapse over it.

These are complicated interactions. It would be fair to ask to what extent might we emerge unscathed from this complexity in terms of our ability to simply describe the tectonic evolution of an orogen. Can we effectively exploit our newly found theoretical understanding? The answer seems to be that as a starting point we need only consider the effects of “push” versus “pull”, in particular where such episodes lead to substantial strains that are imposed on the scale of the entire orogenic lithosphere. In these cases tectonic mode switches will fundamentally affect the thermal evolution of the orogen, and precise knowledge as to the thermal evolution of an orogen will reveal the effect of the sequencing of its tectonic mode switches. This is true, however, only if significant strains accumulate before and after the tectonic mode switch takes place, and only if movements before and after the mode switch are sufficiently rapid to allow the thermal structure to relict from the prior history to be carried through into the stage that follows.

9. Push-pull versus pull-push orogenesis

In regions like the Basin and Range Province of the Western United States it can be argued that the lithosphere of the over-riding plate was first subject to overall horizontal shortening (during the Sevier and Laramide orogenies). Then the lithosphere was thrown into overall horizontal extension by the roll-back or seawards retreat of the flexure of the adjacent Farallon subduction zone (Eaton, 1984). We can look at this sequence of events as an example that shows how an orogen can first be constructed and then collapsed (Coney and Harms, 1984). Or we can regard this as an example of how an orogen may be subject to an overall “push-pull” sequence because of the behaviour of an adjacent subduction zone. According to this latter view, orogens do not have a single constructional phase after which they collapse (cf Dewey, 1988). Orogens can be constructed then torn apart, reconstructed, and then disrupted once again. All orogens are routinely afflicted by such tectonic mode switches, albeit in many cases on time scales much shorter than those we have previously taken into account.

This insight led us to our quite different views as to the nature of orogenesis. In both modern and ancient mountain belts the sequencing of the tectonic mode switches that took place during their evolution define characteristic ‘fingerprints’. The fundamental characteristics of an orogen may be shaped by these tectonic mode

Fig. 5. Evolution of a “pull-push” orogen occurs in two stages. First, extreme extension on a lithospheric scale can lead to elevated geothermal gradients across extensional ductile shear zones and detachment faults of very large areal extent (cf Wernicke, 1985). Heat is advected into the system as the result of the rise of magma and hot fluids.

Fig. 6. The second phase of the evolution of a “pull-push” orogen. In the “pull” phase elevated geothermal gradients develop across lithosphere-scale extensional shear zones. These shear zones may complexly fold during the “push” phase, developing complexly overprinted trains of recumbent and/or upright folds with the extensional shear zone as their carapace. Isograds adjust to overprint synforms, while antiforms rapidly cool. The deeper levels of the cusped synforms adjacent to the thrusts should thus record a thermal pulse, while antiforms ‘freeze in’ the microstructures related to the previous extensional history.

switches, depending on the magnitude and rate of lithospheric stretching or shortening both before and after individual mode switches, and upon how rapidly motion was taking place, again both before and after the mode switch takes place. The nature and duration of tectonic mode switches fundamentally influences the thermal evolution of an orogen, and these thermal influences directly or indirectly determine the processes that take place within it. For example, as we argue below, it is evident that orogens affected by abrupt “push-pull” mode switches are characterized by high-pressure metamorphism, whereas orogens affected by abrupt “pull-push” mode switches are characterized by high-temperature metamorphism, magmatism and anatexis.

The notion that orogens are first constructed and that thereafter that they collapse was a natural outgrowth of a simple view that can now be refuted. The technology-aided resolution of the nature of active tectonism, and the level of detail of new knowledge as to the evolution of ancient orogens, compel us to move on to a more nuanced understanding of orogenesis. In doing so it will be critical to be far more discriminating in using terms such as “syn-orogenic” and “post-orogenic” and better yet to assign those terms to the dustbin. As noted above there can be several episodes during which an orogen is “constructed” just as there can be several episodes during which lithosphere-scale extension tears a newly created orogen apart: with

Alpine orogenesis a case in point. Gravitational energy driven collapse of an orogen can occur in conjunction with slab roll-back, and can also be considered in conjunction with the effect of stress guides that allow an orogen to be pulled apart. Gravitational energy driven collapse of an orogen can occur continually throughout convergence, and is not restricted to an artificially defined so-called post-orogenic phase.

10. Pull-push cycles in the Precambrian ‘metal’ orogen

At the time these ideas began to emerge, we were conducting research in outcrops of the Palaeoproterozoic (1.8–1.5 Ga) orogenic belts, in Broken Hill, NSW, and in the Mount Isa inlier, in NW Queensland, Australia (Betts et al., 2002, 2006; Betts and Giles, 2006). In the context of the ideas being developed in this paper, these could be seen to be “pull-push” orogens, in the beginning subject to ~200 million years of extension, with some minor inversion events, culminating in a major extension event at ~1.58–1.60 Ga, immediately prior to the onset of compressional orogenesis. The simple comparison with the modern Alpine–Himalayan orogen, although often made, could thus be seen to be irrelevant.

We have suggested that such highly extended regions developed extensional shear zones that were potentially regional in extent (Fig. 5, cf Wernicke, 1985). Below the shear zone, where extreme

Fig. 7. Giant recumbent sheath folds have formed as the result of “pull-push” orogenesis, as inferred by Venn (2001) at Mount Robe in the outcrop of the Palaeoproterozoic “metal” orogen at Broken Hill. In the “pull” phase regional extensional shear zones formed (Fig. 6). During the later “push” phase the extensional shear zones were recumbently folded, and now define the carapace of the recumbent structures indicated: (a) the geometry of a giant south plunging recumbent migmatite-cored sheath fold, at the end of the first compressional stage which involved ~N–S shortening; and (b) this giant sheath fold has been refolded by even later ~E–W shortening during another (unrelated) phase of compressional orogenesis. Shortening and re-thickening of the crust took place but now in a direction almost orthogonal to as shown in (a). Evolution of the “metal” orogen did not stop at this point thus resulted in a complexly overprinted giant sheath fold, with geometry schematically illustrated as in (b). Because the structure is south plunging the northern Mount Robe synform marks its lowermost structural levels, and the southern Mount Frank antiform marks its uppermost structural levels.

stretching has taken place, we expect widespread occurrence of high temperature metamorphism, migmatitisation and anatexis. This occurs as a direct result of exhumation and because mafic magmatic activity associated with decompression melting of the underlying asthenosphere advects heat to higher levels of the crust (cf Sandiford, 1989; Collins, 2002). An abrupt mode switch (to a period of compressional orogenesis, or “push”) after a period of intense stretching can lead to profound shortening, with the previously formed extensional shear zone becoming recumbently folded (Fig. 6), and in more extreme circumstances, with ongoing deformation leading to the formation of km-scale sheath folds (Fig. 7a).

Mega-sheath folds of such extensional shear zones will be cored by migmatites and pegmatites. The carapace of these km-scale structures will be defined by the now refolded extensional shear

zone itself. In the case of the ‘metal’ orogen, as it is exposed at Broken Hill, these sheath folds are typically elongate in a ~N–S direction, with the enveloping surface to the axial plane fabrics of the sheath folds striking in ~E–W directions. Even later ~E–W shortening of these giant sheath folds took place (Venn, 2001), folding these axial plane fabrics into upright folds, and developing km-scale fold interference structures. These structures have complex outcrop patterns, and the 3D form of the now multiply refolded carapace shear zone is only schematically represented (Fig. 7b). Although there is still mapping that must be done before we can capture the detail of such complex 3D structures, there are many potential examples evident throughout in the Palaeoproterozoic “metal orogen” as exposed at Broken Hill, Australia (Nichols, 2001; Venn, 2001), or at Mount Isa. Such structures may typify “pull-push”

Fig. 8. The evolution of the Palaeoproterozoic “metal” orogen at Mount Isa region can also be described as involving a “pull-push” orogeny. A sequence of stacked rift basins formed during the extension stage of the history. In (a) the overall tectonic environment at ~1.6 Ga is shown; and in (b) at the end of the “pull” phase. Prior extension had caused uplift of the asthenosphere and partial melting that led to magmatic underplating, now evident in a seismic refraction profile as a transitional velocity layer (TVL). We suggested that mafic magmas underplated the extended crust during the Mount Isa Rift Event (or MIRE). During later shortening (c) a wedge geometry developed, interpreted here to have developed as the result of thrust imbrication of the original TVL. This chisel-shaped geometry caused more surficial levels to be scraped off during shortening and these were overthrust, forming a classic thin-skinned fold and thrust belt (c). This developed into more pervasive crustal shortening as time went on. This figure (modified from Lister et al., 1997; see also Betts et al., 2002, 2006; Betts and Giles, 2006) was developed to explain crustal seismic velocity distribution based on a large scale refraction experiment, in conjunction with a reflection seismology transect, surface mapping and structural analysis (Drummond et al., 1998; MacCready et al., 2006). This was part of the Mount Isa Tectonic Synthesis Project carried out by the Australian Geodynamics Cooperative Research Centre.

orogens, and similar structures may be evident in other “pull-push” orogens, for example in the Appalachian gneiss domes (e.g. Chester Dome, in New England, USA).

Typically the mode switch that takes place at the culmination of a “pull-push” orogeny is marked by a period of static mineral growth during high-temperature metamorphism. The magnitude of the

Fig. 9. The accretion model for “push-pull” cycles during orogenesis, based on a diagram from [Rawling \(1998\)](#). In (a) a rolling back subduction zone is about to encounter a continental ribbon. In (b) the over-riding plate has been switched to a period of horizontal shortening, during which the over-riding oceanic back-arc basin is obducted. In (c) a giant megathrust has sliced the top of the continental ribbon, allowing the weight of the lithosphere beneath to subduct the bottom part of the continental ribbon, allowing roll-back of the facing subduction zone to recommence. In (d) the facing subduction zone has renewed rapid roll-back, which causes intense extension of the terrane-stack in the over-riding orogen. This in turn led to exhumation of newly formed high-pressure rocks, and the stranding of thinly sliced remnants of the first obducted basin in NE New Caledonia. Roll-back continued until the Norfolk Ridge was encountered, at which time New Caledonia was subjected to a second “push-pull” cycle, leading to the second period of ophiolite emplacement and its eventual stranding once lithosphere-scale extension was renewed. This accretion/roll-back mechanism allows explanation of multiple “push-pull” cycles during convergent orogenesis, since each accretion event is associated with its own “push-pull” cycle.

associated thermal pulse may be a function of the rate at which the lithosphere was stretching prior to inversion, and the rapidity with which later shortening commences. If sufficiently rapid motions are involved both before and after the tectonic mode switch, the thermal regime established during the preceding extensional epoch will be carried over into the subsequent period of crustal shortening. Ongoing metamorphism may then overprint structures formed during the shortening stage, producing characteristic complexity and confusion as to the earlier link with extension. In the language of tectonic sequence diagrams (Forster and Lister, 2008) “pull-push” inversion cycles are typified by $SZ F_R \Delta$ cycles, where SZ refers to a ductile shear zone fabric, F_R to a subsequent period of recumbent folding, and Δ refers to a temporally distinct static episode of metamorphic mineral growth that can be inferred from the microstructure. Forster and Lister (2003) show that $SZ F_R \Delta$ cycles are characteristic of the extensional metamorphic welt that defines the Otago Schist.

Of course refolded migmatite-cored sheath folds are not the only types of structures that develop during “pull-push” orogenesis. There are a host of other structures that also potentially characterize such orogens. A detailed study of the tectonic evolution of the Mount Isa region led to the conclusion that a later formed thin-skinned fold and thrust belt may have been thrust westward over a mylonitic detachment formed during intense stretching at ~ 1.6 Ga (Fig. 8a–b). This conclusion was reached after analysis of a seismic reflection study, including in addition a refraction transect and a detailed structural analysis along this 260 km traverse (MacCready et al., 2006). The mid-crustal Goncharov refractor (Fig. 8c) can be explained by a doubling up by thrust imbrication of a transitional velocity zone formed as the result of the underplating of mafic magmas formed during the prior extensional epochs. The essence of this hypothesis requires re-utilisation of a major extensional detachment during the initiation of later crustal shortening. Tectonic shuffling along this structure will lead to curious juxtapositions

Fig. 10. In (a) accretion occurs as the result of the operation of giant megathrusts. An ophiolite and its underlying sub-arc mantle is thrust over a continental ribbon that is inferred to have lain to the north of India, on the subducting Indian plate. Collision led the arc to be overthrust, and eventually a giant megathrust sliced the restraining continental ribbon free from the down-going slab. This enabled roll-back to recommence and the ultra-high-pressure (UHP) rocks were exhumed as the result. A detachment fault formed in the approximate location of the earlier thrust, and the UHP rocks were exhumed beneath this structure (b) as the slab “delaminated” and while the subduction hinge rolled back. As shown this model requires intrusion of an asthenospheric wedge immediately below the accretion megathrust. Such a juxtaposition would have immediate thermal implications, including volcanism, anatexis, hot fluids and metamorphism. This diagram was modified from one originally submitted as part of Lister et al. (2001) to explain the evolution of the Tso Moriri metamorphic core complex, but removed before publication of this paper on the grounds that it was geodynamically unrealistic. The figure should be compared with Fig. 8 of Lister et al., 2001). See text for further discussion.

of lithologies from a variety of different crustal depths (reflected in variation of peak temperature during metamorphism).

11. Push-pull cycles in Alpine orogens

In contrast to orogens typified by “pull-push” cycles, many segments of the modern Alpine–Himalayan orogen appear to involve “push-pull” sequences. A “push-pull” cycle begins with a period of lithospheric shortening, for example typified by the development of a lithosphere-scale terrane-stack, with crustal rocks being thrust deep into the lithosphere along individual major thrusts. It is immaterial whether or not the actual thrust surface is a part of a subduction zone: more often than not we suspect that this is not the case. A major thrust in a terrane-stack is capable of accumulating the relative displacement required, and low geothermal gradients result because of the juxtaposition of individual slices in the terrane-stack. Subsequently, the terrane-stack may be distended as the result of extension driven by roll-back of an adjacent slab. The newly formed high-pressure lithologies are sheared as a result and dragged rapidly back to surficial levels beneath major regional detachments and/or extensional shear zones. This constitutes a simple and effective mechanism to explain the formation, and (shortly thereafter) the exhumation of newly created high-pressure metamorphic rocks.

The “push-pull” scenario outlined above explains many field relationships observed and/or reported from high-pressure terranes: a) the ubiquitous development of thinly-sliced tectonometamorphic stratigraphy; b) the radically different pressure-temperature-time histories that can be inferred for individual tectonic slices; c) the

location of high-pressure terranes in locations distal to the subduction zone active at the time of their formation; and d) the close and commonly observed association temporally and spatially between eclogite-blueschist terranes and stranded onshore remnants of ophiolite sheets. The “push-pull” mechanism has advantages in that: a) it does not require abrogation of basic physical concepts in terms of the potential effects of local buoyancy contrast (see below); b) there is no dependence on local buoyancy contrast in terms of either exhuming material from mantle depths, or from at any level within the crust (since the driving force comes from outside of the system); c) it can explain the exhumation of dense rock, such as slivers of peridotite, from deep in the lithosphere (again since the driving force comes from outside of the system); and d) it explains the remarkable tectonic shuffle zones that in some places have been are misidentified as mélanges on major tectonic contacts.

The assertion that local buoyancy contrast plays no role in this mechanism sets us in opposition to all most models that set out to explain how the exhumation of high-pressure rocks is achieved. The mechanism proposed here does not require corner flow (cf Cloos, 1982). Nor does it require a subduction channel (cf Ganne et al., 2006). Nor is channel flow (cf Beaumont et al., 2001, 2004, 2006) in any way involved in the equation. High-pressure rocks do not need to be subducted to great depth and then mysteriously work their way back to surficial levels by burrowing (cf de Sigoyer et al., 2004), or to be uplifted by buoyancy driven diapiric motion or return flow (cf Wijbrans et al., 1990; Chemenda et al., 1995, 2000, 2001; Boutelier et al., 2004; or Warren et al., 2008). Exhumation driven by slab roll-back is all that is required. It should be noted that slab roll-back is

Fig. 11. Accretion as the result of the initiation of a new subduction zone, showing the schematic evolution of the high-pressure rocks of NE New Caledonia (cf Schellart et al., 2006; Schellart, 2007). In (a) a change in the motion vector of the Pacific plate causes the subduction hinge to advance, which throws the over-riding plate into compressional orogenesis. Obduction of the “back-arc” lithospheric wedge stack subjects a continental ribbon to high-pressure metamorphism. In (b) soon after, a thrust forces lithosphere to sufficient depth to trigger the onset of subduction, marked by rapid roll-back (Schellart, 2004b), leading to distension of the overlying terrane-stack. This inversion produces detachments that dissect the lithospheric wedge stack and exhume the newly formed high-pressure eclogites and blueschists beneath stranded remnants of the previously obducted back-arc lithosphere.

driven by the density differences between the cold subducting lithosphere and the surrounding asthenosphere, so buoyancy contrast does play a role, albeit at a much larger scale.

12. The accretion/roll-back model for push-pull cycles during orogenesis

All that the accretion/roll-back model requires for this “push-pull” mechanism to operate is a temporary interruption to the convergence facilitated by subduction. Imagine a subducting slab rolling back towards a sequence of continental ribbons, for example (Fig. 9). Once the slab rolls back to the point that a relatively buoyant continental ribbon, island arc, or oceanic plateau arrives at the subduction zone hinge, the operation of the subduction zone is hindered and it can no longer so readily accommodate convergence. The subduction hinge is thus pinned. Under many circumstances plate boundary stresses will require that convergence should continue, however, so this movement still must be accommodated. Deviatoric stress levels begin to rise, until the system of interacting plates either reorganizes, or the system yields to accommodate these changed boundary conditions. The lithosphere over-riding the subduction zone may be comparatively weak, and it may thus fail, and in consequence, this is where these movements now concentrate. The over-riding plate begins to shorten, and individual terranes stack as they overthrust one upon the other (Lister et al., 2001).

Once this process begins, the crust and lithosphere of back-arc basins will be obducted. The over-riden footwall may be forced to great depth. Finally, the material hindering subduction will be accreted, either as the result of the operation of a giant megathrust (Figs. 9 and 10), or because a new subduction zone is initiated (Fig. 11). For either circumstance, the act of accretion transfers the blocking material to the over-riding orogen and allows renewed roll-back of the blocked subduction zone to commence. Roll-back in turn triggers lithosphere-scale extension in the over-riding terrane-stack, and rapid exhumation of newly formed high-pressure metamorphic rocks will take place. Thinly sliced remnants of the obducted ophiolite become stranded onshore above detachment faults that slice through earlier formed thrusts and thrust-associated mylonites. And, as shown in Fig. 9, this processes can happen over and over again. Each accretion event is associated with its own “push-pull” cycle, with: i) shortening during compressional orogenesis including obduction of back-arc basin oceanic crust, and folding and thrusting; ii) and thereafter accretion followed by extension and exhumation triggered by renewed slab roll-back.

The accretion/roll-back model for a “push-pull” cycle as outlined above was first proposed by Rawling (1998) and utilized by Rawling and Lister (1999, 2002) in considering the tectonic evolution of the eclogite-blueschist belt in New Caledonia in the SW Pacific. It was evident that the mechanism naturally explained the well-recognized association of Tethyan ophiolites with eclogite-blueschist belts. In the specific example of New Caledonia the accretion/roll-back model considered westward roll-back of an east-dipping subduction zone, and the effects that ensue during and after successive encounters of the retreating slab with each of two continental ribbons (Fig. 9). Each encounter leads first to a period of crustal shortening, and terrane-stacking, and thereafter to accretion. Accretion in turn facilitates renewed roll-back, crustal extension and distension of the terrane-stack. In consequence, the newly metamorphosed blueschists and eclogites that are formed as the result of obduction are shortly afterwards, rapidly exhumed.

For the past decade, the model proposed by Rawling (1998) has featured in numerous presentations discussing the exhumation of high-pressure rocks driven by slab roll-back. A slightly modified version of a key illustration was recently reproduced (on the front cover of Cloos et al., 2007 and by Baldwin et al., 2007 in the same volume), for example. This model thereby differs little from that

proposed by Brun and Faccenna (2008). Rawling's giant megathrust accretion/roll-back model is shown in Fig. 9, with a small but significant modification, namely the implicit (more or less permanent) subduction of crustal material as the result of the operation of a giant megathrust. The megathrusts slice through the obstructing crust on the subducting plate, and thereby allow renewed slab roll-back by ‘delamination’.

There is a significant deficiency in this model however: this is not in respect to the mechanism whereby accretion takes place, but in respect to the predicted location of the focus of subsequent extension. As drawn, the kinematic evolution of the geometry explicitly requires the accreted material to be juxtaposed against a wedge of inflowing mantle asthenosphere (Fig. 10). Brun and Faccenna (2008) adopt the same model, and they also note that this juxtaposition has fundamental thermal and mechanical implications since the accreted material is immediately “*Heated from below by the asthenosphere that flows into the opening mantle wedge*”. The problem is that there is little or no evidence for the immediacy of such effects, either in terms of volcanism, anatexis, fluid flow or metamorphism. Therefore we have not pursued this model *sensu stricto*.

Instead we seek to explain why effects as listed above are found in locations more distal to the active subduction zone. We reconsidered details of the megathrust accretion model in terms of mechanical effects associated with subsequent roll-back model and concluded that thermal and mechanical effects associated with accretion by giant megathrusts ensure that such effects are restricted to the back-arc (cf Brun and Faccenna, 2008). The inflowing asthenospheric mantle wedge (Fig. 10) is not geodynamically realistic, since asthenosphere uplifted to the levels required by this model would partially melt, and the effects of such a magmatic event would be immediately evident. A revised model was published (Lister et al., 2001, Fig. 8) showing roll-back of a delaminating slab driving exhumation of high-pressure metamorphic rock in the back arc region, where thermal effects associated with advecting magma and hot fluids can readily explain overprinting Barrovian metamorphism.

In the case at hand the ribbons involved formed much earlier than the period of tectonism in question. They were the result of Mesozoic extension at the eastern margin of Gondwana, as the west-dipping Pacific slab rolled back toward the east (Lister and Etheridge, 1989; cf Schellart et al., 2006). In this model the easternmost ribbon is the Norfolk Rise. The nature of the westernmost ribbon inferred by Rawling and Lister (1999, 2002) is disputed (Schellart et al., 2006). Nevertheless it may include fragments of continental origin from the Gympie terrane (cf Aitchison et al., 1998) and may continue south to the Three Kings Rise.

We also note that tomographic data is consistent with alternative and quite different models that explain accretion as the result of the formation of new subduction zones (Fig. 11). Schellart et al. (2006) and Schellart (2007) considered this evolution in the context of a reconstruction of the tectonic evolution of the SW Pacific. They conclude that terrane-stacking was set in motion as the result of a swerve in Pacific plate motion (with effects as shown in Fig. 9). This swerve caused the hinge of the descending Pacific plate to advance, forcing abrupt tectonic mode switches in the over-riding plates. In the case of New Caledonia a switch took place from overall extension and back arc spreading, to overall shortening (Schellart et al., 2006). The first of two major ophiolite obduction events took place at this time (Rawling and Lister, 2002) as the result of westward overthrusting of the former back-arc of the subducting Pacific plate. The high-pressure metamorphic belt of NE New Caledonia was the result (Fig. 10a).

In summary, while we conclude that the act of accretion may indeed involve development of a new megathrust that transfers the restraining buoyant crust to the over-riding terrane-stack as shown in Fig. 9, this is only one way to allow an existing subducting slab to recommence “roll-back”. Alternative mechanisms need also be

considered: for example as shown in Fig. 9. A new subduction zone may develop if one of the underthrust slices penetrates to a sufficient depth to allow a Raleigh–Taylor instability to be triggered (Schellart, 2004b). When this happens the newly formed subduction zone will begin to rapidly founder. Schellart (2004a,b) shows that relatively rapid slab roll-back may then take place (Fig. 10b), causing rapid extension during this initial period (cf Lister et al., 2001; Schellart, 2004a,b; Schellart et al., 2006; Stegman et al., 2006). In consequence the terrane-stack in the over-riding lithosphere is readily dismembered. Even diamond facies mantle peridotites can be rapidly exhumed as the result of this distension. Local buoyancy contrast plays no role in this mechanism.

13. Alternative theories for the formation and exhumation of high-pressure rocks

A subduction zone provides an easy mechanism conceptually to drive rocks down to great depths, and to explain why these rocks eventually suffer high-pressure metamorphism. The difficulty is then to provide a mechanism that can realistically explain their subsequent exhumation. Here we take note that any such mechanism must naturally explain: a) why high-pressure metamorphic rocks outcrop with structural relations as observed, in locations that are far from the active subduction zone; and b) the factors that underlie the prevalent association of blueschist and eclogite belts with ophiolite sheets that formerly over-rode the high-pressure terranes.

The model advocated here meets those criteria. The effects of accretion followed by roll-back allow precise explanations of many aspects of the formation and subsequent exhumation of high-pressure metamorphic rocks: a) in respect to the timing of their exhumation shortly after their formation; b) how these rocks can be formed in exactly the same tectonic architecture as that in which they are subsequently exhumed; and c) why the locations in which these rocks typically outcrop are typically distal to the subduction zone that was active at the time of their formation. Not one of the variously postulated alternative mechanisms for the formation and/or exhumation of high-pressure rocks meet all three of these constraints.

Most models for the formation and subsequent exhumation of high-pressure metamorphic rocks do not take into account the overall context of a particular tectonic environment in attempting such explanations. This leads to many different issues for there is “a devil in the detail”. For example in the case of the subduction channel advocated by Ganne et al. (2006): a) there is no direct evidence for subduction in the ‘channel’ in question; b) tectonic reconstructions are precise enough to allow the assertion that there never was subduction in the direction of motion suggested; and c) the direction of relative movement inferred by these authors can be explained otherwise, since it is entirely consistent with orogen-scale extension inferred on several other grounds. Most models omit essential elements of the tectonic architecture, for example, the association of blueschists and ophiolites, which is often-noted throughout the Tethyan ophiolite belts (e.g. in New Caledonia, Rawling and Lister, 1999). Furthermore most models fail to provide a convincing explanation for the location of ophiolites and eclogite-blueschist belts in positions that are distal to the subduction zone that can be inferred to have been active during their exhumation.

There is thus a great deal of debate as to the origin and subsequent exhumation of high-pressure terranes, and models as advocated in this paper are hotly contested. The counter arguments can be flawed in that they begin with the assumption that the occurrence of high-pressure metamorphic rocks marks the position of ancient subduction zones, but provide no other reason than the assertion that this is where such rocks form. Such reasoning is circular. There is no reason why high-pressure metamorphic rocks should not form in ancient subduction zones, but they can also form on lithosphere-scale thrusts. The requisite pressures

can be attained if movements in excess of 100–200 km have taken place on such structures. It may be that this is a merely a question of nomenclature, but subduction zones as typically illustrated involve far greater movements, and penetrate far deeper into the asthenosphere. In fact the pressure–temperature conditions estimated by metamorphic petrologists almost all lie within the P–T envelope that we expect within a lithospheric-scale terrane-stack, even for diamond facies conditions.

It is also important to realize that it is not necessary to call on refrigeration adjacent to a subducting lithospheric slab to explain relatively low temperatures at high pressures, in particular if these pressure–temperature conditions are only transiently attained. Cooling can also result because of the juxtaposition of multiple thrust slices, and this will rapidly reduce the effective temperature gradient in any terrane-stack, even one formed in a tectonic environment with an initially high geotherm. Most high-pressure terranes are exhumed within just a few million years of the metamorphism that sets them apart, so there is no chance that thermal relaxation on a time scale an order of magnitude longer than that observed could raise the geothermal gradient sufficiently to obliterate the low-temperature/high-pressure assemblages.

In respect to the exhumation and exposure of high-pressure rocks, the role of lithosphere-scale extension driven by slab roll-back is currently passed over almost universally in favour of hypotheses related to buoyancy, channel flow, or local extension during convergence (e.g., Chemenda et al., 1995, 2000, 2001). Platt (1986, 1993) and Platt and Vissers (1989) provide a clearly written and well-argued expostulation of alternative mechanisms. Platt (1993) describes the limiting constraints. He writes that: “*The exhumation of high-pressure metamorphic rocks requires either the removal of the overburden that caused the high pressures, or the transport of the metamorphic rocks through the overburden.*” Erosion of shortened and thickened crust, may be involved but the mechanisms proposed need also include, either:

- 1) “corner flow” (Karig, 1980; Cloos, 1982; Ernst, 2001) – leading to the progressive ejection of material from a subduction channel (cf Ganne et al., 2006). We comment that although there is no doubt that such a mechanism could explain occurrences of high pressure rocks as identified in Franciscan mélanges, it is equally possible (considering the works of Jayko et al., 1987, or Shervais et al., 2004) that tectonic shuffle zones have operated in the terranes in question.
- 2) “buoyancy” (e.g. Wijbrans et al., 1990; Jolivet et al., 1994, 2003) – a mechanism that is often proposed to allow deeply subducted rocks to escape from their surroundings, and to rise back through the mantle to crustal depths. Once the material rises to crustal levels other mechanisms of exhumation are then invoked. However we comment that in terms of what is encountered at outcrop scale, local buoyancy contrast cannot be called upon to drive the motion of relatively small lenticular bodies of rock up gently dipping shear zones in ways as advocated by Ring and Layer (2003) or de Sigoyer et al. (2004). Such buoyancy driven burrowing requires a critical mass, and rheological contrasts far greater than those currently inferred in shear zones. The surrounding rocks would need to be very weak to allow this mechanism to operate. This is true even if the lenses were invariably encased in weak serpentinite, which in any case they are usually not. The shear zones would also need to have been steeply dipping so as to allow the magnitude of the resolved shear stress that can derive from local buoyancy contrast to have been non-negligible. We conclude that local buoyancy contrast is highly unlikely to have driven small and thin lenticular bodies along what appear to have been gently dipping structures. In most cases propositions based on this mechanism smack of “*deus ex machina*” noting <http://en.wikipedia.org/wiki/Deus_ex_machina> that “*The Greek tragedian Euripides is notorious for using this plot device as a means to resolve a hopeless situation.*”

Fig. 12. A simple schematic that illustrates some of the geometries and kinematics involved in terrane-stacking and subsequent lithosphere-scale extension. We define *Mode I* inversion cycles as involving reversals of movement, but both shortening and later distension preserve the same terrane-stack (a–e). Shuffling leads to a thinly sliced tectonometamorphic stratigraphy preserving exotic slices remnant from the “push” stage of terrane-stacking (as illustrated in Figs. 1 and 3). We define *Mode II* inversion cycles as involving: (d) first the stacking of terranes; and (e) thereafter extension and consequent distension of the terrane-stack. In (f) renewed compression with opposite vergence in the sense of motion causes cascades of recumbent folds to form. Each terrane is still separated by an extensional shear zone, but this is now recumbently folded. In (g) thereafter, a new generation of extensional shear zones form, and these shear zones that overprint the recumbent fold trains, leading to the development of individual recumbent folds with highly attenuated limbs. These structures thus mimic fold-nappe geometries but they have a quite different origin and their kinematic significance is fundamentally different to that of the fold-nappe model.

3) “extension” – for example utilizing lithosphere-scale dislocations that drag the high-pressure rocks back towards the surface, as proposed in this paper. Platt (1993) however ignored this mechanism and restricted his focus: i) to extension driven by “the forces associated with contrasts in surface elevation” for example in the upper part of an accretionary wedge thickened by underplating (cf Davis et al., 1983; Platt, 1986); and ii) to extension that “may affect the whole lithosphere in a region of intracontinental convergence, if surface elevation has been increased by the removal of a lithospheric root”. In this second case Platt (1993) notes that “extension may be accompanied by magmatism and an evolution towards higher temperature during decompression of the metamorphic terrain”. We note that the same applies to a terrane-stack affected by lithosphere-scale extension, as proposed in this paper, and we therefore conclude that the role of lithosphere-scale extension needs be reconsidered.

In many respects the type of data needed to resolve this debate will come from the combination of structural geology, metamorphic petrology, and microstructure-focussed geochronology. There are now several examples of high-pressure and ultra-high-pressure terranes that involve a thinly sliced tectonometamorphic stratigraphy (e.g. Avigad, 1992), and the elucidation of the detail of the pressure-temperature-time evolution of these individual slices should provide the critical information that would allow firm conclusions to be reached. It is already evident that more complex P–T paths will be necessary if we are to explain the observed relations between metamorphism, fabric, and microstructure in such zones (Wakabayashi, 2004; Forster and Lister, 2005; Beltrando et al., 2007). It is necessary also to incorporate the detail

evident in studies focussed on the emplacement of Franciscan as well as Tethyan ophiolites (Wakabayashi and Dilek, 2000; Dilek, 2003; Wakabayashi and Dilek, 2003).

14. Orogen-scale tectonic shuffle zones

The simple model advocated by England and Thompson (1984) did much to influence modern tectonic theory, but took no real cognizance of the effects of deformation and/or movement on major structures during orogeny. Therefore we set out to provide a slightly more realistic alternative, which we illustrate in Fig. 12. This is a simple model of domino-like shuffling in terrane-stacks. No scale is given, for such a model is applicable over a range of scales from that of a lithospheric terrane-stacks to that of a typical tectonic shuffle zone encountered in a field investigation.

The most potent predictions of the simple models illustrated in Fig. 12 are their quite specific predictions as to geometry. A mode I inversion cycle (as illustrated in Fig. 12a–e) starts with the stacking of individual tectonic slices (or geological terranes) during progressive shortening, leading to vastly over thickened continental crust. The nappe pile may subsequently be extended with the locus of extensional movement either parallel to or at a small angle to the existing terrane boundaries. In this case existing faults and/or shear zones may be reactivated, but because they do not move exactly in the same plane, lenses of relatively high pressure rock may be stranded below extensional detachments, attesting to a cycle of “push-pull” tectonics (Fig. 2). The pre-existing nappe pile and associated stratigraphic columns can become highly attenuated by extensional shear zones and detachment faults during this process.

If we follow the application of this simple model into a second “push-pull” cycle, several circumstances might apply. In the simplest case mode I inversion cycles may be repeated several times, as terranes in the previously extended continental crust again thrust over each other, slicing and re-slicing the orogen (Fig. 12a–e), while shifts in the locus of relative movement will produce a predictable tectonometamorphic stratigraphy with each slice having a distinct tectonothermal evolution. A more complex geometry might see inversion crumple previously extended continental crust into upright folds, including upright folds developed on a crustal-scale. Subsequently, steeply dipping normal faults or extensional shear zones might transect these structures (e.g. as in New Caledonia, Rawling and Lister, 1999), producing complexity that we have not attempted to illustrate.

A second scenario supposes that renewed shortening results in a vergence change applied to the extended nappe pile, with the result that crustal-scale cascades of recumbent folds may form. Each tectonic slice is bounded by a recumbently folded extensional contact, defined by a detachment fault or a ductile shear zone (Fig. 12f). Subsequent extensional tectonism develops low-angle detachment faults and/or ductile shear zones that transect these cascades (Fig. 12g). Nappe-like recumbent folds with highly attenuated lower-limbs result, but the kinematics during the earlier period of recumbent folding are not at all related to the kinematics that apply during the subsequent period of extensional tectonism. As noted by Forster and Lister (2008) this provides an explanation for an enigmatic geometry observed repeatedly in the Western Alps (e.g. in the Vanoise Massif). Earlier detachments and/or extensional shear zones are first recumbently folded, in crustal-scale cascades, and then transected by a second set of extensional shear zones. Structural geology has automatically assumed a relation between recumbent folds and underlying or overlying ductile shear zones, and developed a model of progressive evolution (i.e. in the fold nappe model as applied throughout the European Alps). This assumption appears to have been erroneous. Most structures assumed to be fold nappes within the European Alps now appear to be trains of recumbent folds transected by (unrelated) extensional ductile shear zones (cf Fig. 12f).

15. Discussion

The role of tectonic mode switches in determining the nature of orogenesis has engaged our research now for many years. The subject is not static, however, and discoveries continue apace. Important advances have been made using modeling and simulation studies (e.g., Jamieson et al., 1996; Beaumont et al., 2001; Burov et al., 2001; Gerya et al., 2002; Gerya and Stöckhert, 2002; Beaumont et al., 2004; Burg and Gerya, 2005; Gerya and Stöckhert, 2005; Beaumont et al., 2006; Warren et al., 2008). The difficulty is that these applications of computer models have been limited by an inability to properly deal with discontinuities in continuous media, and by the limitations of the assumptions made as to kinematic boundary constraints in any particular model. For example the semi-independent mobility of the subduction hinge during roll-back and the ability of the orogenic interface to flow over or to be pushed over the subduction hinge of a rolling-back subduction zone are presently issues that are not taken into account. The other issue that has been difficult to take into account is the rheology of real rocks, since this rheology involves complex interactions between dynamic hardening and/or softening, and the competition between the storage of elastic potential energy and its dissipation as the result of a number of thermally activated processes. Deformation mechanisms also involve mass transfer processes. Thus, whereas modeling and simulation do allow the formulation of particular hypotheses and the testing of their physical viability, there are deficiencies to be overcome before such studies can take their rightful place in terms of providing a virtual laboratory enabling

geologists to accurately predict the outcome of specific geodynamic scenarios.

A second aspect that deserves comment in this discussion is the routine assumption that the pressure–temperature–time evolution followed by a particular rock mass can be exactly constrained by the locus of thermobarometric estimates as to the growth conditions for successions of mineral assemblages. Our understanding of the thermomechanical evolution of orogens increased dramatically as the result of papers written by England (1978), England and Thompson (1984) and Thompson and England (1984). The elegance of these models ensured that to this day metamorphic petrologists adhere strictly to the notion that rocks in orogens follow a simple pressure–temperature loop. But there are now many (contentious) issues that challenge the England–Thompson model in quite a fundamental way. For example the timescales involved in Barrovian metamorphism (Oliver et al., 2000; Faryad and Chakraborty, 2005; Johnson and Strachan, 2006) potentially eliminate models that rely on radioactive heating as the mechanism of heat input (e.g., models as proposed by Jamieson et al., 1996, 1998; Beaumont et al., 2001, 2004, 2006). Modeling and simulation studies need focus on mechanisms of heat input that are consistent with the short time scales now reported. This means that attention is now being paid to: a) advective transport by fluids and/or magma (Ague and Baxter, 2007; Viete et al., 2007; cf Jamieson et al., 1998); or b) the generation of heat as the result of mechanical work during deformation (e.g. England et al., 1992; Burg and Gerya, 2005).

The England and Thompson (1984) model uncritically assumed instantaneous deformation of an orogen, and predicted its subsequent thermal evolution solely on the basis of radioactive heating and erosional exhumation. Should terrane-stacking models apply there would be, of necessity, great changes introduced into the concepts that follow from dedicated application of the England–Thompson model. For example the P–T–t envelope defined by the locus of successive estimates of metamorphic conditions would define nothing more than a succession of transiently attained P–T conditions, with each shuffle of the terrane-stack leading to an additional assemblage in the sequence. Beltrando et al. (2007) provide a first indication that this can be the case, demonstrating pressure pulses and a geodynamic scenario consistent only with the terrane-stacking model. The time-scales involved in the terrane-stacking model are also far shorter than needed by radioactive heating models, since variation in pressure can be quite rapid, and temperature is influenced by advection of heat in fluids and magma introduced during active tectonism. This is consistent with the several lines of evidence that demonstrate time-scales for metamorphism orders of magnitude shorter than that required by the England–Thompson model (e.g., Camacho et al., 2005; Ague and Baxter, 2007; Viete et al., 2007).

We emphasize that not everything discussed in these pages has been totally resolved and understood. For example one of the strangest aspects of this evolving story is that (in the language of tectonic sequence diagrams, Forster and Lister, 2008) tectonic mode switches involving “push-pull” inversion cycles are typified by $F_R \Delta SZ$ cycles. A period of recumbent folding [F_R] may not always signify crustal shortening, but occasionally it can be demonstrated to be the case (e.g. Rawling and Lister, 1999, 2002). High-pressure metamorphic mineral growth at or about the time of the tectonic mode switch seems to be particularly common, in particular marked by periods of (very short-lived) static growth [Δ] of porphyroblasts (Forster and Lister, 2005). These minerals commence growth immediately prior to the time that the rock mass is cut by extensional ductile shear zones [SZ], and growth of some porphyroblasts typically continues into the period of shear zone operation. It is also not immediately evident why the timing of these short-lived metamorphic mineral growth events should be synchronized over such very large distances.

We also emphasize that there are many examples of phenomena as discussed in this paper other than those described: most of these

examples are untapped in terms of their potential to further elucidate the role of tectonic mode switches in affecting the nature of orogenesis. For example the modern Andean chain exhibits the effects of a “pull-push” mode switch. Jordan et al. (2001) show that >3000 km of the strike length of the Andean chain was thrown into lithospheric extension from ~28 Ma, with extension apparently increasing in intensity southwards. Using concepts developed in this paper this can be explained by accelerated westward roll-back of the hinge of the adjacent subduction zone. If this is correct then roll-back appears to have accelerated during a period of rapid convergence, coincidentally shortly after the time that eastward roll-back of the Scotia Arc began to generate ocean crust (Cunningham et al., 1995). At ~20–18 Ma, a switch to horizontal compression took place leading to widespread basin inversion marking the beginning of construction of the modern Andes.

There are also many issues of scale and process to unravel, and as well, debates need to take place that are in essence related to terminology. Some of these are related to a lack of understanding of the large-scale movement picture, for example, there are many cases where extension takes place synchronously with thrusting and net convergence. In the Alps “*foreland basin migration in the external zones was synchronous with extensional shearing unroofing the eclogite*” (Wheeler et al., 2001). It can be argued that therefore these orogens display examples of simultaneous extension and shortening, but this inference is correct only in part. Geometry requires that there must always be a basal thrust that marks the edge of the convergent boundary. To some extent, even if the volume of rock considered is merely that part of the orogen immediately adjacent to the frontal tip of the thrust, there must be rock that is subject to horizontal shortening at the same time as other rocks are being subject to horizontal extension.

It is not correct to assert that any thrust is by definition overlain by a mass of rock being subject to horizontal shortening. Lister et al. (2001) illustrate the geometry to be expected during a surge of collapsing orogenic crust, with the entire over-riding plate subject to horizontal extension for the entire time that it thrusts over the foreland. Forster and Lister (2005) illustrate how several episodes of metamorphism can result in this way. A surge can take place each time a new frontal thrust breaks, since this provides a weak basal fault allowing collapse of thrust sheets stacked up during a preceding period of crustal and/or lithospheric shortening. Forster and Lister (2005) show that this domino-like stacking followed by domino-like collapse leads to tectonic shuffle zones, and a thinly-sliced tectono-metamorphic stratigraphy. Each tectonic mode switch is marked by the breaking of a new thrust, a surge of the orogen over the foreland, and the conversion of previously operating thrusts into low-angle detachment faults. Convergence takes place throughout, independent of whether or not the overlying orogen is extending or shortening.

16. Conclusion

Plate tectonic theory evolved based on the notion of rigid plates. Theories as to the nature of orogenesis thus lacked a critical datum, and many doubted that the internal motions within orogens could ever be related to the plate tectonic framework. Perhaps as a result current theories as to the nature of orogenesis have not taken the implications of semi-independent motion of the orogenic interface into consideration. Field evidence that potentially manifests the consequences of such orogen-scale events is often relegated to the category of a phenomenon of only local significance, and therefore not important to the elucidation of the tectonic evolution of the orogen as a whole.

The convergence of two points (one on each plate, with each point distal to the orogenic zone) does not determine the tectonic mode in the intervening orogen. This behaviour is determined by the dynamics

of interaction across the orogenic zone, with four main modes of operation. Using simple terms to describe the interaction with the hinge of the adjacent subducting plate, and using this marker as a datum, these mechanisms can be described as: a) “push against”; b) “push over”; “pull away from”; or d) “collapse over”. A change from one tectonic mode to another will result in large areas of the orogen being subject to a switch from wholesale horizontal shortening to horizontal extension, or *vice versa*. Tectonic mode switches can take place even during steady overall convergence (e.g., during the early stages of the India–Asia collision). Where the behaviour of an adjacent slab determines the outcome, the tectonic mode within the orogen will be determined by processes taking place at or near the interface, as well as in response to changes in the global pattern of relative plate motions.

Tectonic mode switches are readily induced by accretion events. The arrival of a continental ribbon, oceanic plateau or island arc at the intervening subduction zone will change the relative motion of the subduction hinge in respect to the over-riding plate, with the result that either “push-back” or “hinge-advance” will take place. The orogen will then undergo a period of lithosphere-scale shortening. This period of shortening can be terminated by the act of accretion since this transfer once again allows “hinge-retreat”, “roll-back” or “pull-back” to take place. The orogen can thus be abruptly switched from lithosphere-scale horizontal shortening to lithosphere-scale horizontal extension. Several such tectonic mode switches can take place during a period of overall steady convergence of the same tectonic plates.

The concepts we advocate provide a logical framework allowing explanation for the differences between many modern and ancient orogens, e.g., why some orogens are typified by high-pressure metamorphism while others are a showcase for regional high temperature low-pressure and/or high temperature metamorphism and anatexis. These concepts also allow resolution of many of the issues that surround the existence of thinly sliced and/or recumbently folded tectono-metamorphic stratigraphy, in particular why most (if not all) exposures of high-pressure and ultra-high-pressure metamorphic rocks occur in or near such orogen-scale tectonic shuffle zones.

The sequencing of tectonic mode switches determines the thermal evolution of an orogen, in particular if significant strains accumulate before a mode switch takes place. Orogens subjected to abrupt “pull-push” sequences are characterized by intervening episodes of high-temperature metamorphism, whereas orogens subjected to “push-pull” sequences exhibit intervening episodes of high-pressure metamorphism. In particular we note that many segments within the modern Alpine–Himalayan chain are typified by repeated “push-pull” cycles. The accretion of a continental ribbon, an island arc, or an oceanic plateau, is preceded by a period during which terrane-stacking and obduction of oceanic basins in the over-riding plate sends crustal rocks deep into the lithosphere. Terrane-stacking itself then leads to high-pressure metamorphism.

Accretion can take place either as the result of the operation of a giant megathrust, or as the result of a new subduction zone being initiated. The act of accretion leads to an initial period of rapid slab roll-back. Slab roll-back leads to extension in the adjacent orogen, distending the over-riding terrane-stack, and rapidly exhuming thin tectonic slivers that have previously been metamorphosed at deep levels in the lithosphere. The tectonic shuffle zones that form in consequence allow explanation of enigmatic disrupted tectono-thermal stratigraphic stacks that are found in classic localities in many mountain belts.

Acknowledgments

M.A. Forster acknowledges the support of an Australian Post-Doctoral Fellowship and currently an Australian Research Fellowship

provided by the Australian Research Council (ARC). Research support was provided by ARC Discovery Grants DP0449975 “Revisiting The Alpine Paradigm: The Role Of Inversion Cycles In The Evolution Of The European Alps”, DP0343646 “Tectonic Reconstruction of the Evolution of the Alpine–Himalayan Orogenic Chain”, and DP0877274 “Tectonic mode switches and the nature of orogenesis”. The paper greatly benefited from reviews provided by John Wakabayashi and George Davis (and now includes specific sentences provided by these reviewers). The encouragement of numerous colleagues including Peter Betts and Peter Cawood is gratefully acknowledged.

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