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Tectonic mode switches and the nature of orogenesis

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A R T I C L E I N F O

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A B S T R A C T

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.

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 indentor 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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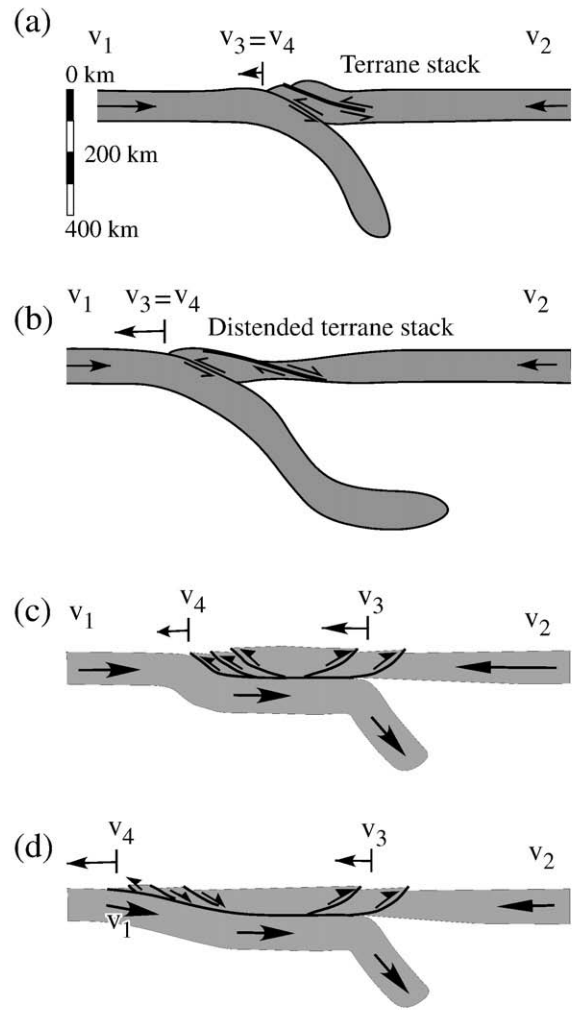

Fig. 1. Velocities that determine tectonic mode switches: v_1 the velocity of the subducting plate, v_2 the velocity of the over-riding plate, v_3 the roll-back velocity of the subduction hinge, and v_4 the velocity of the orogenic interface. In: (a) terrane-stacking in the over-riding plate above a 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) [$v_3 = v_4 > v_2$] faster than the over-riding plate is able to advance; (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