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On uplift and exhumation during convergence

Kurt Stüwe[1] and Terence D. Barr

Department of Earth Science, Monash University, Clayton Victoria, Australia

Abstract. A simple kinematic model is used to illustrate the vertical motions of rocks during convergent deformation and erosion at the surface. It is shown that rocks may move upward or downward in the crust, depending on the relative rates of erosion and thickening and depending on their initial depth in the crust. Exhumation during thickening can only occur if rapid denudation accompanies the thickening process. During homogeneous thickening with erosion that is elevation dependent, the initial depth from which rocks can be exhumed is only determined by the density distribution in the column and is independent of erosion or thickening rates. The maximum initial depth, from which rocks can be exhumed, is of the order of 30 km or less. There is therefore no conflict in the observation of synchronous exhumation and convergent deformation if the peak pressure of rocks is equivalent to no more than 30 km of burial. It is also shown that uplift (defined as vertical motion of the surface with respect to a reference level, for example the geoid) and exhumation (defined as vertical motion of rocks with respect to the surface) may follow different patterns in time and that the difference between the two evolutions may be a useful indicator of the exhumation process. The model serves to emphasize the important differences between uplift and exhumation which are often not distinguished in the literature.

1. Introduction

Exhumation of rocks in mountain belts during convergence has been widely documented, for example, by cooling histories [*Zeitler et al.*, 1993; *Hodges et al.*, 1993; *Neubauer et al.*, 1995] or through the interpretation of reaction textures [e.g., *Carson et al.*, 1997]. There is also a direct coupling between the grade of metamorphic rocks and surface elevation with rocks from the deepest crustal levels outcropping often near the axis of highest surface elevation [e.g., *England*, 1981; *Dahlen and Barr*, 1989]. However, neither surface uplift nor convergent deformation can bring rocks closer to the surface and rapid denudation must be invoked as a process that accompanies deformation (Figure 1).

Because of this coupling between deformation and denudation, many geologists do not discriminate between the processes of (surface) uplift and exhumation. For example, the common (and potentially misleading) terminology of "thrusting out" or "squeezing metamorphic domes to the surface" are still well entrenched in the literature. They may be misleading because they withdraw attention from the real exhumation process (the denudation) and attribute (mistakenly) the deformation itself to be the exhuming process. Uplift, however, is often not considered at all. Some of this confusion was clarified by *England and Molnar* [1990], but their study focused on the confusion around uplift and did not discuss details of the depth or time dependence of the vertical velocity field. Moreover, despite their study, the terms "uplift" and "exhumation" are still used very loosely in the literature, even despite an increasing number of studies dealing with coupling of these processes [e.g., *Koons*, 1987; *Zhou and Stüwe*, 1994; *Montgomery*, 1994; *Rowley*, 1995; *Batt and Braun*, 1997].

Here a simple kinematic model is presented that can be used to evaluate the vertical velocity field in the lithosphere during thickening and erosion. The model is designed to illustrate how various vertical motions in a vertical column may differ as a function of some very simple parameters. The model is clearly too simplistic to explain the details of any particular orogenic belt, but the model does illustrate some of the potential implications of different but concurrent vertical motions in mountain belts. As the terminology remains a much confused issue and as this paper aims to clarify it, we begin with some definitions.

2. Definition of Terminology

England and Molnar [1990] defined "surface uplift" or just "uplift" as the vertical motion of the surface with respect to a fixed reference level, for example, the geoid or the surface of an undeformed reference lithosphere. In their definition, they refer to vertical motion of the surface on a regional scale, that is, averaged over an entire orogen or significant parts thereof. "Exhumation" was defined by *England and Molnar* [1990] as vertical motion of rocks with respect to the surface, so that positive exhumation means rocks move closer to the surface, and negative values for exhumation, or exhumation rates, mean that rocks move farther away from the surface, that is, are buried.

"Exhumation" is used here in the strict sense of *England and Molnar* [1990], and we abbreviate the rate of exhumation with v_{ex}. This meaning corresponds to the derivation of the word as defined in the Oxford dictionary and it corresponds to what we can interpret from geobarometry or, if assumptions about the thermal structure of the crust are made, from geochronology. It also corresponds to the widely accepted meaning among metamorphic, igneous, and structural

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[1] Also at Institut für Geologie, Universität Graz, Graz, Austria.

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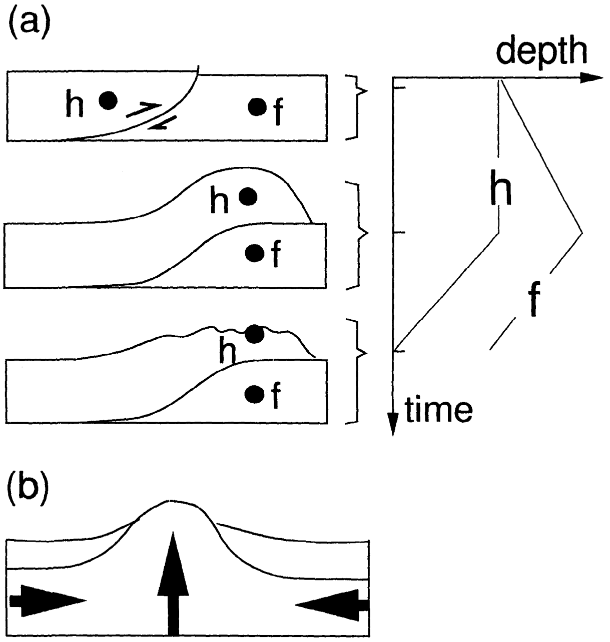

Figure 1. Two examples illustrating the depth changes that rocks experience during thickening and denudation and how uncritical use of "uplift" for both processes may cause confusion. (a) Three steps during the formation of a ramp anticline. Ramp anticlines are often interpreted to be associated with exhumation. However, the depth - time diagram on the right of the three schematic cartoons shows that it is only the denudation and not the thrusting that causes depth decrease. If the anticline forms not near the surface but as part of a thickening pile at depth, then both the hanging wall (labelled h) and the footwall (labelled f) of the anticline may experience depth increase in the second step and third step of the cartoon sequence. (b) A cartoon modified from *Ratschbacher et al.* [1991], which has been used to illustrate the "uplift" history of the Tauern Window in the eastern Alps. While the diagram is correct in portraying the correct vertical motions, it may be misleading as the horizontal and vertical arrows describe two different processes that are not necessarily coupled. The horizontal arrows describe displacement of rocks due to deformation. A vertical arrow matching these two would have to point downward. The upward vertical arrow describes displacement of rocks due to denudation.

geologists, and we therefore retain its use. However, it is pointed out that this definition is not that given by the *Glossary of Geology* [*Bates and Jackson*, 1987], nor is it the one understood by geomorphologists, who restrict the use of "exhumation" only to features that were previously at the surface; that is, an old landscape or a fossil can be exhumed, but a granite (which has never been on the surface) can not.

"Denudation" is used here to describe removal of material from the surface, either by erosion or tectonically. It is called v_{er} here. In the absence of other processes, 10 m of denudation will correspond to 10 m of exhumation. However, it is important to note that denudation is not necessarily that same as exhumation. For example, if rapid overplating accompanies deundation at the surface, rocks may actually get buried during denudation. Alternatively, rocks can exhume without denudation, for example by buoyancy forces relative to the surrounding rocks [e.g., *England and Holland*, 1979].

"Uplift", abbreviated as v_{up} will be used to describe vertical motion of the surface with respect to a reference level. However, the use of uplift in this paper will deviate from the definition of England and Molnar [1990] inasmuch as we will not use it in a regionally averaged sense. That is, the surface at different sides of a fault can have different uplift rates, even if the mean uplift is negligible. Uplift is difficult to document, but it has been attempted to constrain it by geomorphological, paleontological and paleobotanical means [e.g., *Forest et al.*, 1995].

Finally, "uplift of rocks" or "rock uplift", abbreviated as v_z, is the vertical motion of rocks with respect to a reference level. It is virtually impossible to document rock uplift in nature unless exhumation and uplift rates are known, but it is a useful parameter for calculating particle trajectories with respect to a fixed reference frame.

3. A Kinematic Description

Consider a simple one-dimensional column undergoing homogeneous thickening in response to an external driving force and denudation at the surface (Figure 2). The assumption of homogeneous thickening has successfully been used in many studies to describe first-order kinematic processes, and the

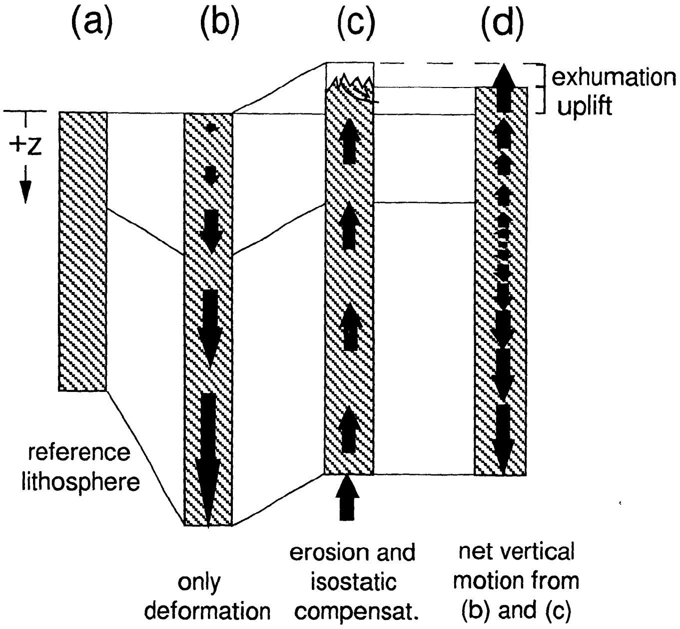

Figure 2. Schematic diagram illustrating the vertical motions discussed in this paper (modified from *Zhou and Stüwe* [1994]. Arrows are vectors of the vertical velocity field. (a) Undeformed reference lithosphere. (b) Vertical movement of rocks as the consequence of thickening. (c) Vertical movement of the column due to isostatic compensation of both the thickening and erosion at the surface. (d) The net velocity field of rocks during simultaneous thickening and erosion as given by the sum of Figures 2b and 2c.

assumption has recently been elegantly justified by *Platt* [1993]. It is assumed that the column is in isostatic equilibrium at all times. The vertical velocity field of such a system may be described by

$$v_z = \frac{dz}{dt} = v_{ro} - \dot{\varepsilon}\left(z + H\right) \tag{1}$$

in which $\dot{\varepsilon}$ is the vertical strain rate and z is depth measured positive downward from the surface of an undeformed lithosphere. The velocity v_z is defined positive upward and negative downward. H is the surface elevation above the surface of the undeformed reference column, and v_{ro} is the vertical velocity of the one-dimensional column due to isostatic compensation (defined positive upward). The velocity v_{ro} is the sum of denudation rate v_{er} and surface uplift velocity v_{up} (positive upward) due to isostatic compensation of both the thickening and denudation so that

$$v_{ro} = v_{er} + v_{up} \tag{2}$$

[*England and Molnar,* 1990]. When there is no deformation $v_z = v_{ro}$ and $v_{ex} = v_{er}$. During deformation and denudation, the exhumation rate is given by

$$v_{ex} = v_{er} - \dot{\varepsilon}\left(z + H\right) \tag{3}$$

The second term in (1) describes a depth-dependent vertical expansion of the column as the consequence of thickening (Figure 2b), and the first term describes a vertical translation of the column (Figure 2c).

The isostatically supported surface elevation H (positive upward) can be approximated by

$$H = \delta z_c (fc - 1) - \xi z_l (fl - 1) \tag{4}$$

[*Sandiford and Powell,* 1990] in which f_c and f_l are the thickening factors of the crust and the lithosphere, respectively; z_c and z_l are the initial thickness of the crust and lithosphere, respectively; $\delta = (\rho_m - \rho_c)/\rho_m$ and $\xi = \alpha\ (T_l - T_s)/2$, where ρ_m and ρ_c are the mantle and crustal densities, respectively, α is the coefficient of thermal expansion and T_l and T_s are the mantle and surface temperatures, respectively. Equation (4) was derived for a lithosphere with no internal heat sources [*Sandiford and Powell,* 1990], but more refined assumptions on the thermal structure have a negligible influence on the vertical kinematics [*Zhou and Sandiford,* 1992; *Zhou and Stüwe,* 1994]. If the lithosphere is undergoing homogeneous thickening and denudation at the surface, then the thickening rates of crust and lithosphere are

$$\frac{df_c}{dt} = f_c\dot{\varepsilon} - \frac{v_{er}}{z_c} \qquad \text{and} \qquad \frac{df_l}{dt} = f_l\dot{\varepsilon} - \frac{v_{er}}{z_l}$$

Substituting these two expressions into (4) gives the evolution of surface elevation during simultaneous thickening and denudation:

$$\frac{dH}{dt} = v_{up} = \dot{\varepsilon}(H + A) - v_{er}B \tag{5}$$

where A and B are the constants, $A = (\delta\, z_c - \xi\, z_l)$ and $B = (\delta - \xi)$. *Zhou and Stüwe* [1994] used steady state solutions of (5) to explore the mechanical consequences of the steady state vertical velocity field for the dynamic evolution of mountain belts. Here the time-dependent evolution of all points in the vertical column and surface elevation are explored assuming a constant thickening rate $\dot{\varepsilon}$ in order to compare uplift and exhumation histories and explore the thermal consequences.

In order to do so, an erosion model must be invoked. Erosion is likely to be a function of relief [*Ahnert,* 1970; *Summerfield,* 1991], a description which cannot be considered in a one-dimensional model. As the closest possible approximation in a one-dimensional model, we assume that the erosion rate v_{er} is proportional to elevation so that

$$v_{er} = H/E \tag{6}$$

where E is the erosion parameter, a constant that describes how long it will take to erode a given elevation H. The evolution of surface elevation as a function of time may then be found by integrating (5) with respect to time to give

$$H = \frac{\dot{\varepsilon}A}{\dot{\varepsilon} - B/E}\left(e^{t(\dot{\varepsilon} - B/E)} - 1\right) \tag{7}$$

From (1) it can be seen that for small depths v_z will be positive (describing upward motion of rocks), while for large z the vertical velocity will be negative (downward motion of rocks) (Figure 2d). Thus there will be a transition point in the vertical column where v_z=0 and there is no vertical motion. The depth of this transition point does not need to remain constant. It may move upward or downward during the evolution of the orogen. The transition point is found by substituting (5) and (2) into (1), setting v_z to zero, and solving for z to give

$$z_{(v_z=0)} = A + \frac{H}{\dot{\varepsilon}E}(1 - B) \tag{8}$$

Trajectories of individual rocks may be found by integrating (1) with respect to time (after substitution of the time-dependent variables, e.g., (7)). The result is

$$z = z_i e^{\dot{\varepsilon}t} + \frac{A}{B}\left(1 - e^{\dot{\varepsilon}t}\right) + H\left(\frac{1-B}{B}\right) \tag{9}$$

in which z_i is the initial depth of a chosen rock. Equations (7), (8), and (9) can now be used to describe the vertical motions of various critical points in the lithosphere during thickening and erosion at the surface.

4. Vertical Velocity Field Described by the Model

For the calculations, the following standard values were assumed for the physical parameters: ρ_m=3200 kg m^{-3}, ρ_c=2700 kg m^{-3}, T_l=1280°C, T_s=0°C, z_c=35,000 m, z_l=100,000 m, and α = 3 10^{-5} °C^{-1}. With these parameters, the constants in (7)-(9) are A=3550 m and B=0.1371. A strain rate of $\dot{\varepsilon}$ = 10^{-14} s^{-1} is assumed, and all results will be discussed in terms of this numerical value. However, it is noted that in (7)-(9) strain rate and time are directly proportional, so that changing the strain rate by a given factor changes the time in all calculations by the inverse of this factor.

4.1. Surface Elevation *H*

During thickening and erosion at the surface, the surface elevation will increase (Figure 3). Elevation converges to a steady state for all erosion rates that are larger than that given by $E=B/\dot{\varepsilon}$ (i.e., $E<B/\dot{\varepsilon}$). For larger values of *E*, the erosion rate is smaller, and the surface elevation gain is exponential. Clearly, the latter scenario is an impossible geological situation and is an artifact of the kinematic model. For the assumptions on the density distribution made here, surface elevation converges for erosion parameters smaller than $E <$ 435,000 years. For E=200,000 years, the steady state elevation is reached after about 10 Myr. Interestingly, the rate at which the steady state elevation is reached depends on *B*, but

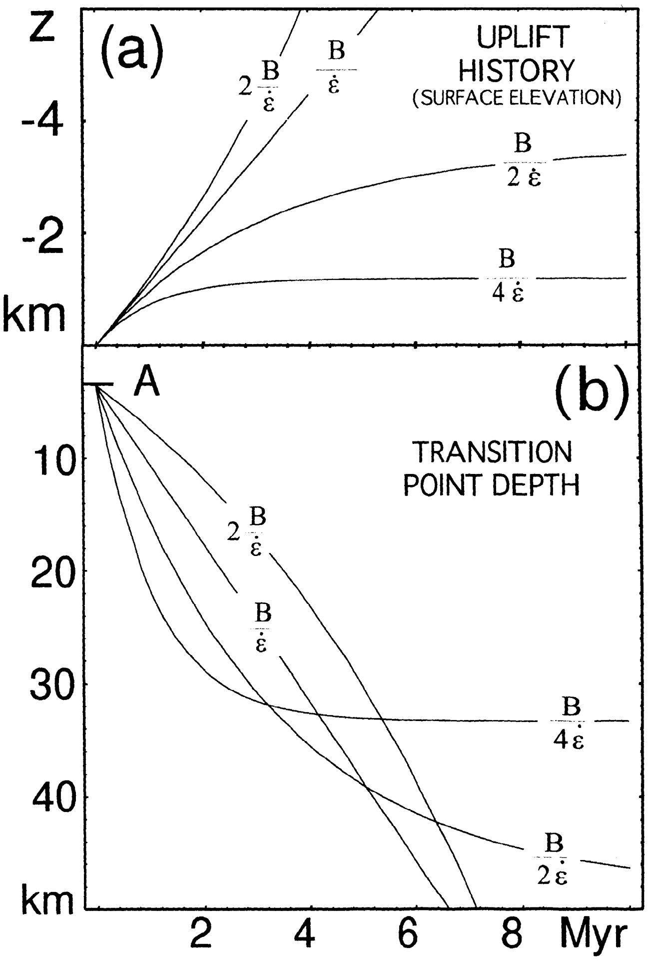

Figure 3. Evolution of (a) surface elevation and (b) depth of the transition point, $z_{(vz=0)}$, during simultaneous thickening and erosion for a thickening strain rate $\dot{\varepsilon}=10^{-14}$ s^{-1}. Both diagrams are drawn for four different erosion parameters *E*. The curves of Figures 3a and 3b were calculated with equation (7) and equation (8), respectively.

the steady-state elevation itself (Figure 3) depends predominantly on *A* (see (5) and (7)).

4.2. Rock Trajectories

During thickening and erosion at the surface, some rocks will be exhumed to the surface, while others will continue to be buried at all times (Figure 4). The deepest rocks that can ever be exhumed are those that have trajectories that converge with the transition point at long times. The initial depth of these rocks z_{imax} can therefore be found by equating (9) and (8), setting $t=\infty$, and solving for z_i. It is given by

$$z_{imax}=A/B$$

z_{imax} is about 26 km for the parameters chosen here but less than 30 km for most reasonable parameter values. Interestingly, this maximum depth from which rocks can be exhumed is independent of erosion and thickening rates. Exhumation commences at later times for larger depths. Rocks from most initial depths exhume only after uplift has ceased and the surface elevation has reached a steady state. Simultaneous denudation and thickening may result in large vertical isotropic sections of the crust that are made up of lower crustal material. Figure 4a shows that 5 km of crustal section initially between 20 and 25 km depth may constitute the majority of the crustal profile after 10 Myr.

A comparison between the depth evolution of individual rocks and the evolution of the surface elevation shows that the two processes follow different patterns through time. Most rocks will be buried during the initial period of rapid uplift which accompanies the onset of deformation. Only rocks that are initially shallower than depth *A* move upward and closer to the surface at the time of uplift.

4.3. Transition Point, $z_{(vz=0)}$

Equation (8) shows that the shallowest depth of the transition point occurs when there is negligible surface elevation ($H\approx 0$). Then, $z_{(v_z=0)}\approx A$ so that only rocks shallower than about 3500 m can move upward during deformation (Figure 1). The transition point $z_{(v_z=0)}$ changes linearly with *H* and therefore converges to a constant depth as elevation reaches a steady state (Figure 3b). During the onset of deformation, the transition point will increase in depth more rapidly for larger erosion rates and more slowly for smaller erosion rates. At later times, the relative depths of the transition point for small and large erosion rates are reversed (Figure 3b). This is because smaller erosion parameters do not allow the development of any surface topography, so that the erosion rate (at this elevation) remains comparably small.

5. Relevance and Geological Examples

The discussion above shows that the vertical motions of the surface (i.e., uplift) and various other points in the vertical column may follow different patterns in time, even in a simplistic model where erosion is directly linked to elevation. One implication of this concerns the interpretation of the

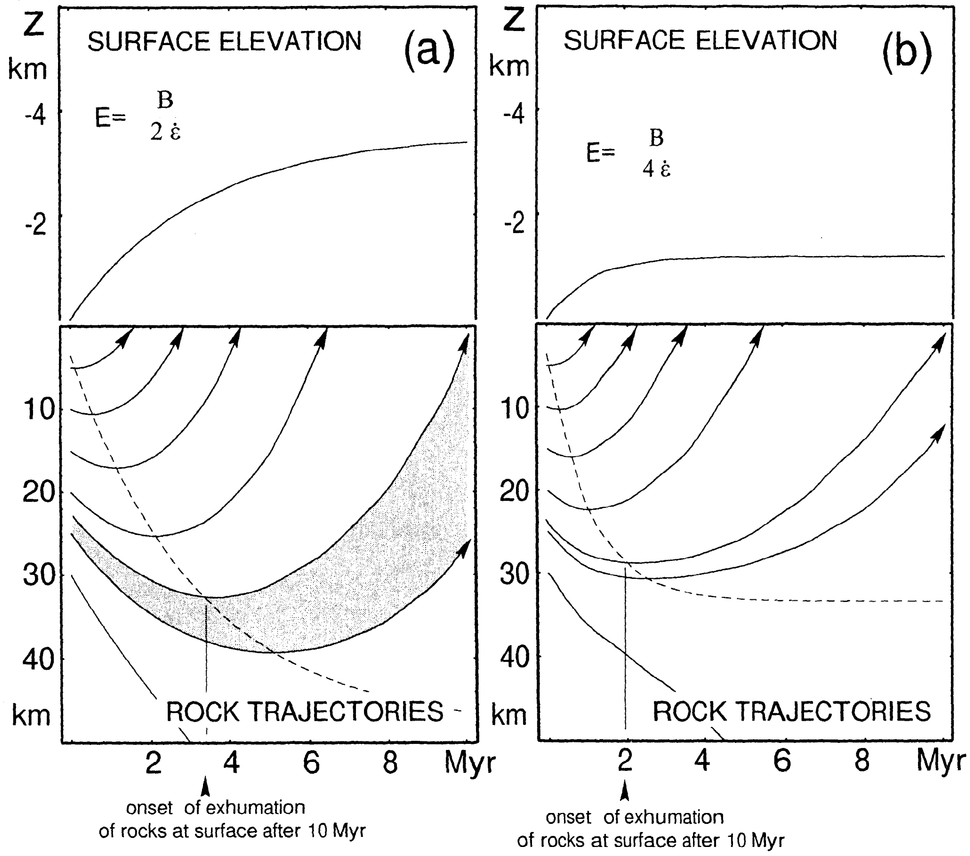

Figure 4. Trajectories for rocks from a series of initial depths (solid lines) (bottom half of diagrams) and corresponding uplift histories (top diagrams). (a) $E=B/2\dot{\varepsilon}$ and (b) $E=B/4\dot{\varepsilon}$ corresponding to two erosion parameters from Figure 3. The dashed lines show the depth evolution of the transition point ($z_{vz=0}$). The shaded region shows that comparably small vertical sections of the crust may form substantial vertical sections after simultaneous deformation and denudation.

geometry of largest-scale structures. For example, consider a two-dimensional section in which every vertical section is described by (7)-(9) (Figure 5). During initial deformation, all rocks with initial depths $z_i > A \approx$ 3500 m will move downward, and therefore downward displacement will be largest in the region of maximum thickening. It is therefore more likely that regional synforms not dome structures form at this stage. Exhumation of the structure may only commence once the transition point $z_{(v_z=0)}$ has travelled to levels below the structure. In this process, formerly synformal structures may be inverted by the processes of denudation

and its isostatic response.

The example of Figure 5 is only relevant for the simplistic model assumptions made here. However, it does illustrate that the interplay of uplift and exhumation may have a profound influence on the shaping of large-scale structures. In the particular example shown in Figure 5, shortening amounts cannot be estimated from the geometry of the dome at the end of the process. Some geological examples are now discussed where uplift and exhumation appear to follow different patterns. Thus, even though the model above may not be directly applicable to them, it does show the first-order effect of crustal thickening and erosion on vertical motions. In addition, the examples below illustrate that care must be taken in the interpretation of their largest-scale geometry.

5.1. The Tauern Window

The Tauern Window of the Eastern Alps is a large tectonic window, in which the lowest units of the Alpine metamorphic pile are exposed. The window also forms the axis of highest topography in the eastern Alps [*Stüwe and Sandiford*, 1994]. Its Tertiary history is often referred to as "the uplift of the Tauern Window" which is generally loosely used for both the processes of uplift of the Tauern Range and the process of exhumation of the rocks in the window [*Ratschbacher et al.*, 1991; *Selverstone*, 1985]. However, the two processes may have occurred at different rates and at different times. The exhumation history is geochronologically and geobarometrically well established [*Cliff et al.*, 1985; *Blankenburg et al.*, 1989; *Zimmermann et al.*, 1994]. The uplift history of the Tauern Range is less well constrained. However, if uplift preceded exhumation, the dome structure of the window may have been caused by the processes of denudation (and isostatic compensation) rather than the

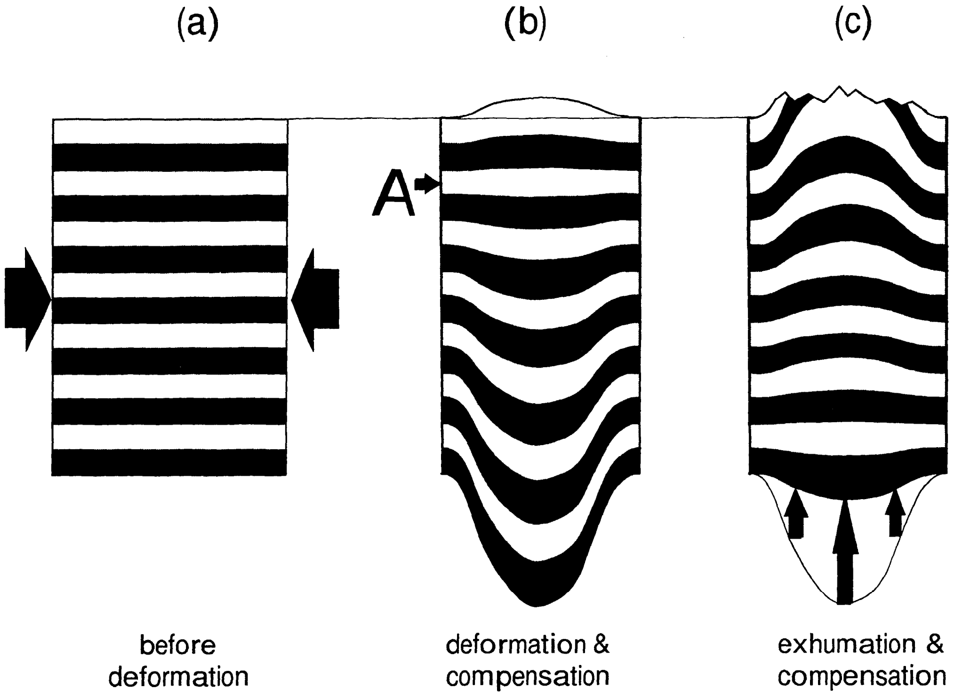

Figure 5. Cartoon showing a possible implication of the model discussed here for the evolution of metamorphic domes. An undeformed reference lithosphere (a) prior to thickening, (b) after thickening and isostatic compensation, and (c) after denudation and isostatic compensation is shown. Depth *A* in Figure 5b indicates the depth of the transition point during deformation (and compensation) alone (see equation (8). Note that the extreme dome shape of the structure at the surface is not been created by deformation but by denudation and its isostatic response.

shortening deformation phases. More detailed application of the model is unjustified, not at least because the eastern Alps are unlikely to have evolved in Airy-isostatic equilibrium and because their geometry is clearly two-dimensional [e.g., *Genser et al.*, 1996]. Regardless, the causes for shaping of the dome will remain contentious until the evolution of both uplift and exhumation is well understood.

5.2. Examples From Ancient High-Grade Terrains

In many ancient low-P high-T terrains of Australia and Antarctica, exhumation of rocks occurred during convergent deformation. This is documented by syntectonic formation of metamorphic reaction textures that record decompression and often form axial planar to shortening folds [e.g., *Stüwe and Powell*, 1989; *Harley*, 1989; *Carson et al.*, 1997]. Many low-P high- T terrains occur also in shield areas where large sections of the crust are made up isotropically of basement gneisses (compare Figure 4a). The model discussed above shows that rocks from initial depths up to 30 km can well be exhumed during convergence. There is therefore no conflict between exhumation and ongoing thickening for rocks that experienced peak pressures equivalent to no more than 30 km of burial. However, the model fails to explain exhumation of rocks during convergence in terrains that have exhumed from much larger depths.

6. Discussion

Clearly, the model discussed above is extremely simplistic and is subject to a number of assumptions that may invalidate its direct application. Perhaps the most fundamental potential fallacies are the assumptions of the thin sheet approximation and that of isostasy. Both assumptions are necessary in the light of the aim of this study, which is to emphasize the discrepancies that may arise between the vertical velocities of the surface and rocks at various depths from even such a simple model. While these differences may be much larger for more refined assumptions, the limitations imposed by these, the simplest of all scenarios, are now discussed.

6.1. One Dimensionality

The model assumes that thickening strain occurs vertically only. Therefore any application of the model implies that convergent strains observed in the field correspond to thickening of the crust and therefore to burial. This need not be so. In two-dimensional deformation geometries apparent shortening may be caused by other processes. For clarity, it is useful to discriminate between two different deformation processes: (-1-) indentation or side forcing and (-2-) basal traction. During indentation, deformation is driven by external forces operating beyond the boundaries of the orogen. Then, the thin sheet approximation may be valid, and convergent

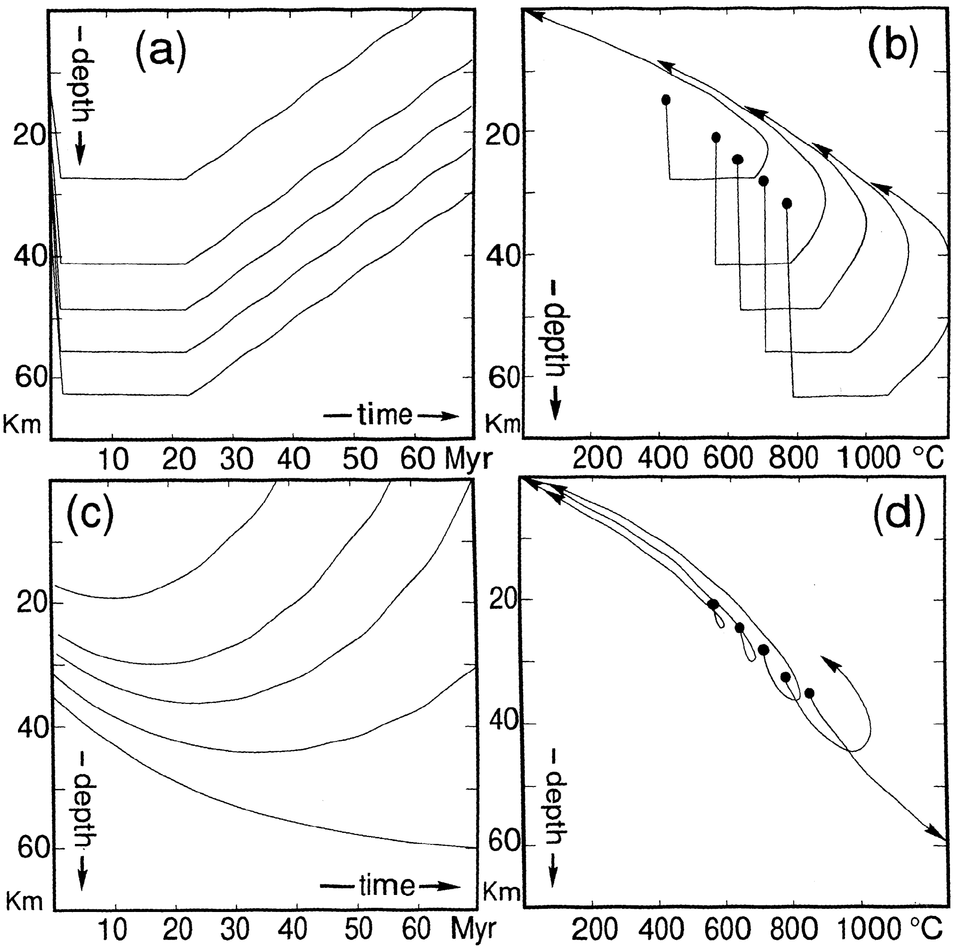

Figure 6. (a) Depth-time and (b) depth-temperature paths of the model of *England and Thompson* [1984]. (c) Depth- time and (d) depth-temperature paths of the model discussed here. In Figure 6b the assumptions for the initial geotherm are the same as in Figure 6a (see text): the surface elevation was calculated with the first term of equation (3), strain rate is $\dot{\varepsilon}$ 10^{-15} s^{-1} and the erosion parameter is E=0.5 $B/\dot{\varepsilon}$. The arrow heads in Figures 6b and 6d indicate the position of rocks after 70 Myr.

strains translate into thickening strains. Even if thickening is by nappe stacking rather than by homogeneous means, only denudation can cause exhumation, while deformation can only cause burial (see Figure 1). Total strains that may be attained by indentation on an orogenic scale are likely to be no larger than 2-3. Basal traction, as, for example, occurs in orogenic wedges [*Platt*, 1986], allows local strains much larger than 3. When basal traction is the driving force to deformation, the model does not apply.

The assumption of one dimensionality also does not allow the implementation of more realistic erosion models. It is well known that erosion is a function of relief and that there may be little correlation of erosion rate and elevation [*Summerfield*, 1991]. Asymmetries of orogens as a function of two-dimensional relief have now been observed [e.g., *Koons*, 1987] and predicted [*Braun and Sambridge*, 1997]. However, this fact does not preclude the basic message of the model, which is to emphasize that exhumation and uplift histories must be considered independently.

6.2. Isostasy

The model discussed in this paper is based on the assumption of isostasy. Therefore denudation rate is determined by elevation, and the depth of the transition point is determined by the density contrasts between crust and mantle. However, it should be remembered that any differences in the evolution of uplift and exhumation will have potential to cause substantial vertical reorientations of large-scale structures. This fact is independent of the processes that caused these differences.

6.3. Thermal Consequences

In order to explore the thermal consequences, a temperature profile was assigned to the initial vertical column and PT paths were calculated during the subsequent kinematic evolution. The results are compared with those of the thermal model of *Englan* *and Thompson* [1984], which differs in its kinemati assumptions inasmuch as it discerns burial and exhumation as two discrete steps separated by a hiatus of 20 Myr (Figures 6a and 6c). For the comparison, all assumptions of the kinematic and thermal parameters made here are the same as those of *England and Thompson* [1984] using their heat source distribution II, homogeneous thickening, and a thermal conductivity $k=1.5\ \mathrm{J\ s^{-1}\ m^{-1}\ K^{-1}}$. PT paths differ substantially between the two models. Both the amount of burial and the amount of heating that individual rocks may experience are substantially smaller in the present model than in a model where deformation and exhumation occur subsequently to each other. This difference is particularly pronounced at shallow levels, which begin to exhume very early in the history, while deeper levels will be buried for somewhat longer times. Indeed, for the parameters used for Figure 6, rocks above about 20 km depth will exhume nearly directly from their initial depth, so that no metamorphic signature may be expected. In contrast, rocks below about 25 km experience a much longer heating phase. Thus, if deformation and exhumation occur simultaneously, PT paths from shallow and deep levels will show larger differences than in a model in which deformation and exhumation occur consecutively.

7. Conclusion

A simple one-dimensional description of the vertical velocity field of rocks during deformation with erosion at the surface shows that the lithosphere may be divided into two parts: an upper part which moves upward with respect to a reference level and a lower part that moves downward. The two parts of the column are separated by a transition point which has zero vertical velocity, but which does not remain fixed in depth. During deformation alone, the depth of this transition point is very shallow ($z_{v_z=0\approx 3500 m). If denudation accompanies thickening, rocks from much deeper levels can move upward and be exhumed. The maximum initial depth from which rocks can be exhumed is only a function of the density distribution in the column and is independent of erosion and thickening rates. It is about 30 km. The model shows therefore that there is no conflict in the observation of concurrent thickening and exhumation if the peak pressures of rocks are no larger than the equivalent of 30 km of burial.

The model illustrates that uplift and exhumations histories may follow different patterns in time and must be considered independently. One of the implications of different uplift and exhumation histories may be that large-scale dome structures may have formed initially as synforms (formed during deformation) and were only subsequently inverted by the exhumation process. This is but one example which indicates that care should be taken in the use of the terminology of "uplift" and "exhumation".

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T.D. Barr, Department of Earth Science, Monash University, Clayton, Victoria 3168, Australia. (e-mail: terence@earth.monash.edu.au)

K. Stüwe, Department of Earth Science, Monash University, Clayton, Victoria 3168, Australia. (e-mail: kstuwe@earth.monash.edu.au)

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