Formation of upwarped mountains by horizontal compression of lithosphere in shear layers model: A review

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Abstract: The understanding of mountain uplift, especially the intraplate ranges and plateaus, still remains insufficient despite advancement in the last decade. Upwarped mountains are one general category, where uplift virtually comes from the bottom by an unspecified mechanism. Several sandbox and finite-width wedge models showed that this upwarping is a natural consequence of horizontal compression of lithosphere. The model of shear layers, presented here, is derived from general theory of plasticity and represents a similar solution of the problem. But its ability to describe deformations in deeper lithosphere can be useful in studying development and changes of mountain roots. Comparison of these models, regarding their specific character, may help to understand overall morphology and tectonics of the mountains.

Key words: mountain roots, mountain uplift, shear layers, upwarped mountains

1. Introduction

The mechanism of mountain uplift in intracontinental space is still not sufficiently understood. There are many definitions of mountains by structure and by manner of uplift, often contradictional in their nature. This way, for example, a concept of folded mountains was discredited by solid proofs that folding is usually unrelated to uplift neither in time nor in character of tectonics *(Ollier and Pain, 2000)*. There is also a category of mountains called upwarped, what means uplift comes from the bottom by generally unspecified mechanism (Fig. 1). Volcanic plumes, delamination of lower lithosphere, mantle flows or isostatic rebound are frequently taken as a case. On the other hand, mountains are usually seen as compressional structures, what is in agreement with definition of plate tectonics as a horizontal compressive system. The most successful in describing upwarping as a natural consequence of compression were numerical or analogue sandbox models *(Buiter et al., 2006)* and certain finite-width wedge models *(Braun and Yamato, 2010)*, specifying frame for physical considerations about uplift of intraplate mountains.

These models, thanks to improved computational methods, had pushed our understanding of upwarping mechanism within compressional regimes. But not well understood remains the fact, how the wedge deformation continues farther downwards. This is not resolved by any contemporary wedge model. The serious limitation of these models appears to be shallow depth and discontinuity at their bases, what does not allow to estimate how mountains are rooted in the lower lithosphere.

Based upon the same principals, but more universal is the model of shear layers, developed from general theory of plasticity *(Nadai, 1950).* By observing the materials, suffering compressional deformation, a mathematical-physical abstraction was developed for use in metal forming industry and civil engineering. The model shows how layers of slip form within a compressed body at the yielding point, creating complicated shear layer field. Patterns of deformation at the field flanks strongly resemble those from real stepped surfaces of mountains as it is also visible on sandbox or finite-width wedge experiments. These characteristics of Nadai's model lead to consideration that it could be applicable to the mountain origin as the supplement of sandbox and other wedge models.

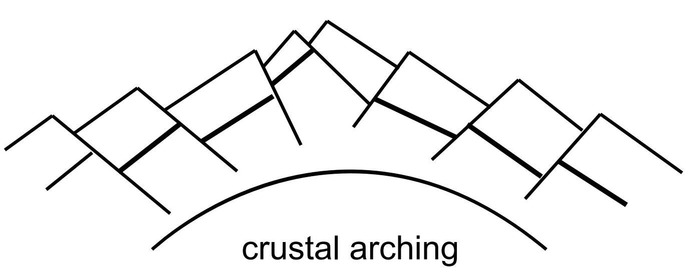


Fig. 1. Schematic drawing of upwarped mountains (`http://www.cliffsnotes.com/study_guide/Types-of-Mountains.topicArticleId-9605,articleId-9583.html`).

2. Model (Nadai's theorem)

The Earth's lower lithosphere is considered to be an elastoplastic material. But in many cases, when deformation in the plastic part of body is much greater than in the elastic, we can assume this elastic part as a solid *(Nadai, 1950)*. In these cases a medium is taken as rigid/plastic, what means that it is mostly rigid except in regions, where yielding has occurred and the limit of plasticity has been reached. This simplification enables mathematical solutions for some specific problems within general theory of plasticity, which also can be applied to the tectonics *(Tapponnier and Molnar, 1976)*.

Consider a prism of rigid/plastic solid under conditions of stress, when the stress has just reached the limit of plasticity and body cannot deform in z direction. In an incompressible material the plastic strains (and the associated displacements u_x and u_y) can be expressed *(Nadai, 1950)* as follows:

$$\varepsilon_x + \varepsilon_y = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} = 0, \tag{1}$$

$$\varepsilon_z = \frac{\partial u_z}{\partial z} = 0, \tag{2}$$

$$\tau_{xy} = \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} = 0 \tag{3}$$

In the unyielded parts of body it is assumed that components of strain vanish (and so does unit shear τ_{xy} for axes x and y) because they are principal directions of stress and strain. If also u_x and u_y are considered as components of velocity vector of flow, ψ represents the stream function and the first equation is satisfied if

$$u_x = \frac{\partial \psi}{\partial y}, \qquad u_y = -\frac{\partial \psi}{\partial x}. \tag{4}$$

Substituting this into the third equation, we obtain the following result:

$$\frac{\partial^2 \psi}{\partial x^2} = \frac{\partial^2 \psi}{\partial y^2} \tag{5}$$

Here, the physical insight enabled *Nadai (1950)* to recognize in this equation the second class equation of a vibrating string:

$$\frac{\partial^2 w}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 w}{\partial t^2} \tag{6}$$

where w is the deflection of string stretched along x axis, constant c^2 the tension stress divided by mass of unit length and t is the time. It is than useful to plot successive configurations of an infinite string at the times t by plotting the values of w along the lines $y = ct = const$ (Fig. 2).

Next, changing variables $x, y = ct$ to new variables m and n by transformations

$$x = \frac{m-n}{\sqrt{2}}, \qquad y = \frac{m+n}{\sqrt{2}}, \tag{7}$$

in Fig. 3 and by substitutions of n and m to these equations (keeping m and n constant), we obtain

$$x = (m\sqrt{2}) - y, \qquad y = (n\sqrt{2}) + x, \tag{8}$$

which represents two systems of parallel straight lines, inclined at angles 45° and 135° with respect of the x axis (Fig. 2).

The similarity between characteristics of the deflected shapes of an infinite string and characteristics of the displacements in a body under the compression is clearly visible and these lines define lines of slip in a compressed body, coinciding with directions of maximum shearing strain *(Nadai, 1950)*. Using this analogy, for symmetrical compression, the dashed lined

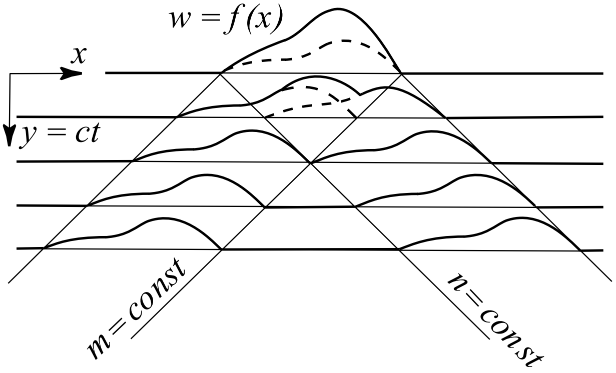


Fig. 2. Deflections of an infinite string by *Nadai (1950).*

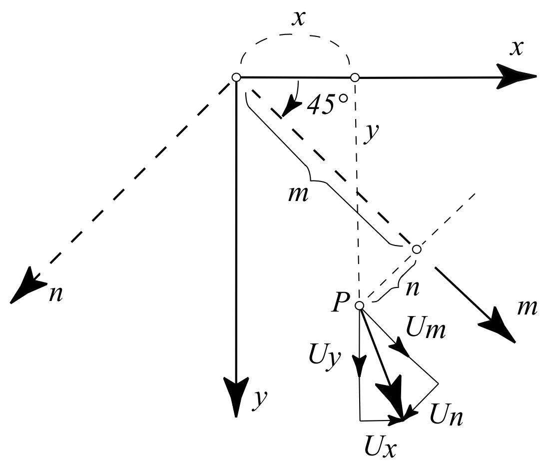


Fig. 3. Transformation of variables, by *Nadai (1950)*.

formation in Fig. 4a can be obtained, representing initial system of two intersecting layers of slip in a compressed body.

During next continual compression, when material is distorted by simple shear, the field slowly changes to a fully lined structure, with central rhomboid and pushed out triangles. The central rhomboid creates only envelope for a rhomboidal net, composed of several parallel layers, in which some are distorted and some are displaced in the x, y plane as rigid bodies (Fig. 4b). It is usually hard to obtain such plastic zones within rigid regions without distortion of the whole body, so these considerations are highly theoretical. For more realistic states the stress slip layers and lines are curved and there is a complex change of hydrostatic stress along them. Variations of hydrostatic stress described by equilibrium equations then provide a basis to determine plastic flow solutions within the deformed plastic body.

3. Application of results to the structure development of upwarped mountains

When we apply shear layers model to the compression of lithosphere, first visible thing is that it does not need any special starting conditions to produce upwarping. Rigid-plastic material and enough pressure are sufficient

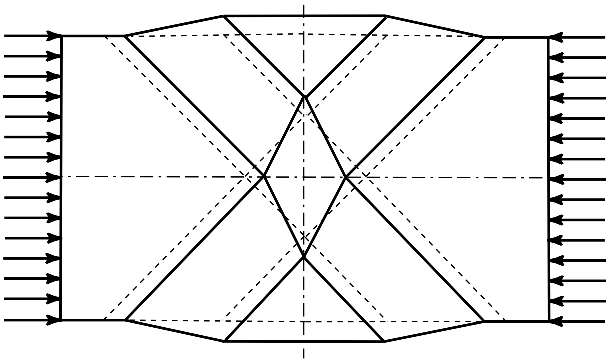


Fig. 4a. Two layers of shear in compressed body, by *Nadai (1950).*

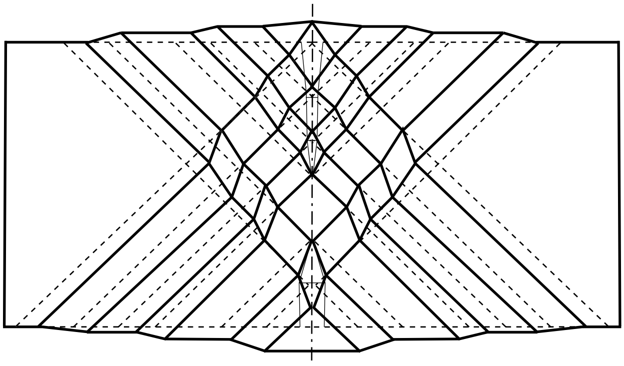
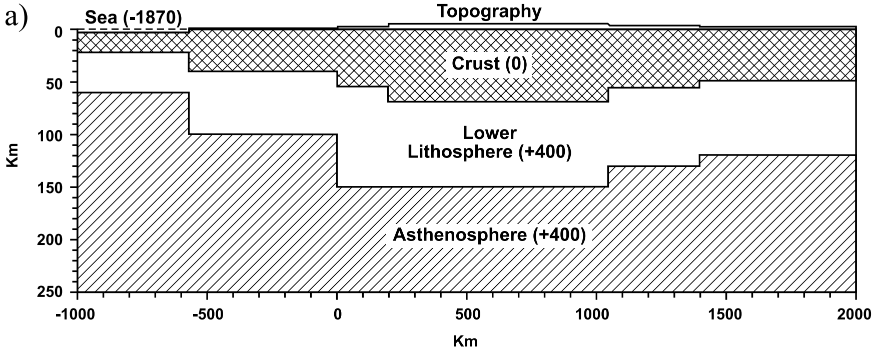


Fig. 4b. Multiple layers of shear in compressed body, by *Nadai (1950).*

to initiate this process. This is very important for origin of majority of intraplate mountains, where no predispositions can be found in lithospheric structure prior to initiation of uplift. Such mechanism is able to create mountain chain in relatively homogeneous lithosphere without presence of any former subduction related fabric. Another significant feature of the model is widespread shear banding, where slip lines intersect themselves in the middle part of the field, forming complicated rhomboidal net. Its tip is pressed down in series of steps at the base of the body, remaining the style how orogenes are rooted in the lower lithosphere (Fig. 5).

Similarly at the top of the body, upper crust forms the stepped surfaces as wedges are pushed up. Because deformation is symmetric along central vertical plane, these surfaces tend to have approximately the same elevation on both sides of the ridge. It is frequently seen in the mountains that elevated surfaces form stepped plains, uplifted remnants of former plain, which occupied given space prior to initiation of upwarping. Due to the geometry of the field, as seen in Fig. 4b, central part of the mountain chain can be principally plateau (Fig. 6a) or ridge toped (Fig. 6b).

a)



b)

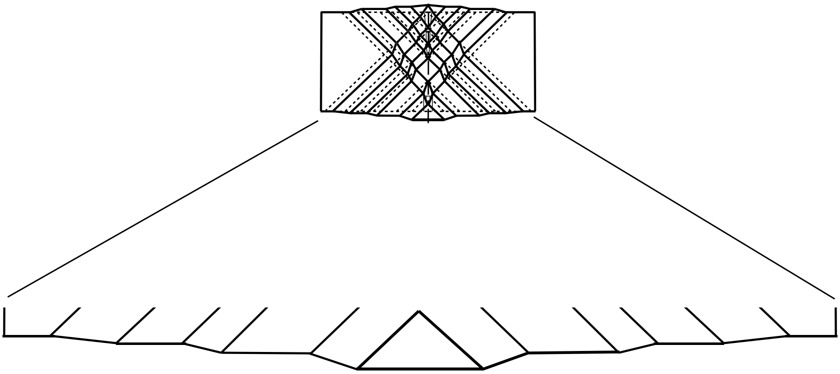


Fig. 5. a) Lithospheric structure of Tibetan Plateau, by *Bielik el al. (2000)* with isostatic compensation and comparison with b) the model of *Nadai (1950)*, isostatic compensation is not considered.

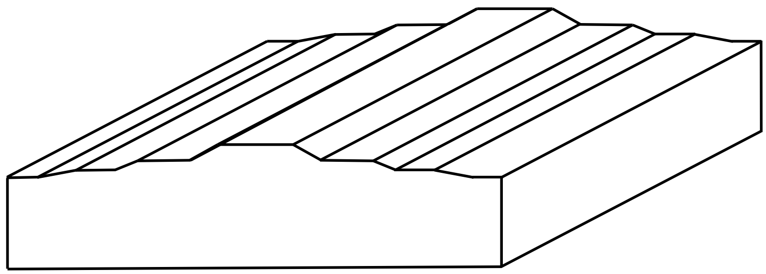


Fig. 6a. Plateau top morphology, derived from Fig. 4b.

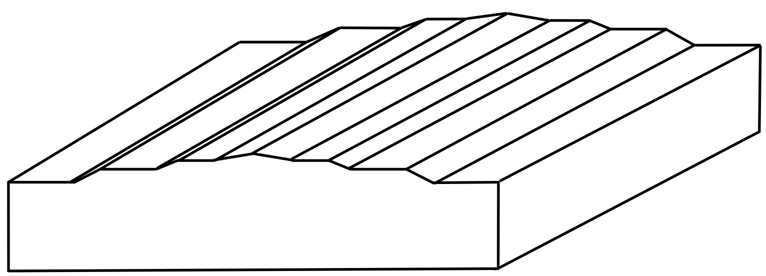


Fig. 6b. Ridge top morphology, derived from Fig. 4b.

The categorization of mountains describe upwarping also as the process, causing fan shaped disintegration of orogene central part (Fig. 1). During this doming, top of uplifted area is in the state of slight extension. The same is visible in Nadai's model and effect is caused by the material escape from zone of deformation. Extension can appear around the ridge top part (Fig. 4b), where upwarping is the most intensive.

4. Comparison with other models

Theory and modelling within this subject had improved in the last decade with improvement of computational methods. From simple Coulomb wedge considerations *(Davis et al., 1983)*, used mostly to explain subduction related orogenes, contemporary sandbox and finite-width wedge models reached realistic state in visualization of mountain building. Numerical sandbox experiments for compression *(Buiter et al., 2006)* show several features, similar to that of shear layers model. The most prominent characteristic is the widespread shear-banding and development of stepped surfaces, typical for the mountain growth (Fig. 7b). However deformation is principally asymmetric and despite qualitative leap in description of upwarping, the model reflects reality only in limited area.

Highly realistic appears to be the finite-width wedge model *(Braun and Yamato, 2010)*, where solution is the wedge upwarping with well developed stepped surfaces of principally symmetric geometry (Fig. 7a).

These characteristics of surface manifestation, common to both computations, are visible also in the shear layers model. What is not present in any contemporary upwarping modeling is an exact insight into deeper structure of mountains. Sandbox and finite-width wedge models are shallow based solutions because they artificially end at the basal discontinuity, where velocity suddenly changes to zero. It is in fact only simplification, deformation should continue also to lower lithospheric levels (Fig. 5). Shear layers model has no limitations in this sense, depth of bottom boundary is controlled by the thickness of compressed block. This feature is in general given by the fact that it does not need specific initial conditions as both

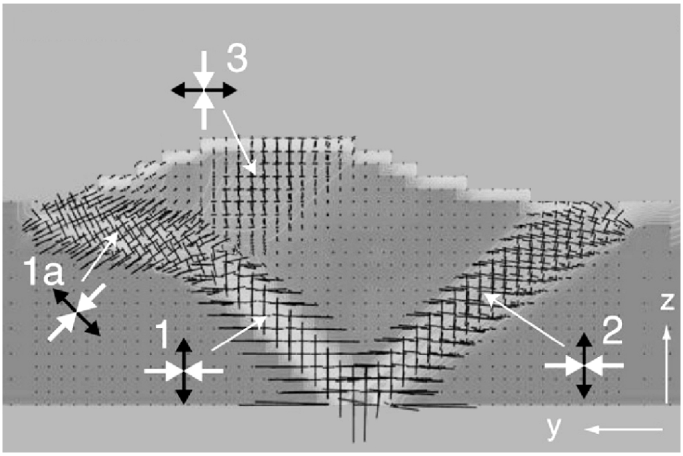


Fig. 7a. Finite width crustal wedge, by *Braun and Yamato (2010).*

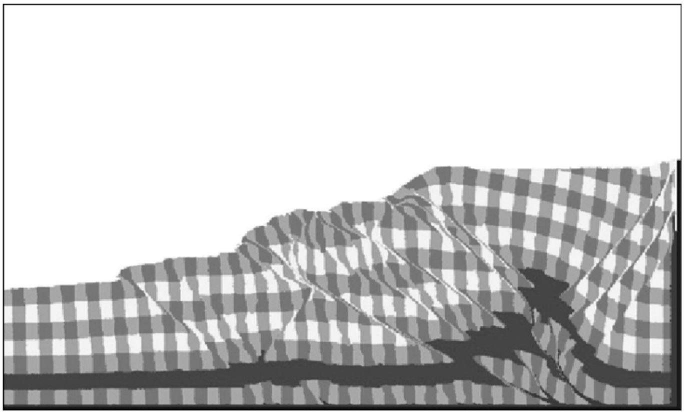


Fig. 7b. Numerical sandbox experiment, by *Buiter et al. (2006).*

compared models (compressing wall, fixed base, limited thickness). As it was mentioned, besides material properties and compression, shear layers model has no other starting conditions and so appears to be much simpler.

5. Conclusions

The attempts to explain mountain building as a consequence of horizontal compression, supported by solid computational methods, started to dominate tectonics during the last decade. Upwarping and horst structure evolution, taken as results of some "inside" mechanisms in the past (plumes, delamination), moved to the state of real physical modelling. Shear layers model is one of the approaches to do by studying shearing in the complex lithospheric wedges. It brings the possibility to visualize several specific elements, characteristic for overall mountain buildup. It shows, as the other wedge models, how double-vergent structure is developed, how upwarping proceeds in steps of flat surfaces uplifted among shear bands, which form inner, inclined lithospheric layering. The ability of presented model to describe deep structure of mountain belts comes from simple symmetry presumption that upwarping wedge in the surface direction must have its counterpart in downward orientation. Other wedge solutions mostly lack insight into the problem of orogene rooting in the lower lithosphere. Disintegration through shearing and extensional pressure release causes melting and may initiate delamination of bottom field tip in its extreme case. In summary, model presented in this paper offers several new aspects regarding the development of intraplate elevations, the understanding of real processes, creating inner structure and topography of the mountains.

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