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# Numerical simulation of a Himalayan profile

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**Abstract** Six numerical models exploring the dynamics of the front ranges in a N-S profile through a biaxial Himalayan collision orogeny are described and assessed. A 4000m high "Tibetan Plateau" with a 3000m deep foredeep is simulated in only "100,000 years" by shortening 200km of a front of an extending Newtonian "India". The Newtonian "sialic crust" is deformed by a 60km deep ramp dipping 45 degrees northwards in a rigid "mantle asthenosphere" moving "northwards" at 10cm/year. A foredeep subsides above the ramp because the northern part of Newtonian "India" can not keep up with the rise of the "Himalayan front".

A soft, low-density region inserted above the rigid ramp rises so slowly that it makes little difference to the surface topography. A larger soft, low-density inclusion in front of the ramp simulates the "High Himalaya" despite not having time to become diapiric. Restricting the area analysed by finite elements to only about 0.1 the width of the "Tibetan Plateau" means that the restricted plateau rises about 10 times faster than a full-width equivalent. This biases the progressive deformation of surface relief far more than its dissipation by gravity spreading (i.e. isostatic compensation is confined to the viscous crust). Various improvements to the model are suggested.

## Introduction

The "continent-continent collision" model for the uplift of the Tibetan Plateau has recently been treated numerically by England and others (England and McKenzie,1982,1983 ; England and Houseman 1985,1986). With the intention of explaining the structure of the interior of the Asian continent, these studies assumed the Indian and Asian crusts to be incompressible non-Newtonian fluids and analysed their collision in three dimensions by means of a thin sheet numerical analysis.

Although these models succeeded in simulating the dimensions of the Tibetan Plateau and its roots (see a stylised "NS" profile in Fig. 1), these workers ignored "India". The realism of their models is therefore limited by their calculations being truncated sharply at a vertical boundary along the mountain front. Furthermore they assume an unrealistic inviscid (perfect) fluid layer beneath their thin viscous "Asia". The isostatic balance in their models is biased to the mantle.

It is too soon to expect much realism from numerical simulations of such complex processes as mountain building. However, other small advances are attempted here by reversing the "inviscid mantle" approach and concentrating on the actual collision zone (Fig.2). The Tibetan Plateau reaches 1000-1500km north of the gland and his various co-workers have already explored the northward propagating margin of the Plateau and our model would need to be inconveniently long to do this. Instead, we therefore concentrate on that part of the Himalayan front ranges outlined in Fig.3a (and illustrated in Fig.2). To do this we confine the plateau with a vertical rigid boundary 160km north of its southern edge.

We first describe the boundary conditions of our basic model and then how it appears to simulate a Himalayan profile when it is deformed for only 100,000 years. We then introduce soft inclusions to simulate the "High Himalaya" and then explain how our boundary conditions biases progressive distortion at the expense of the regressive viscous spreading. To explore this bias we stop the movement of the mantle and find that

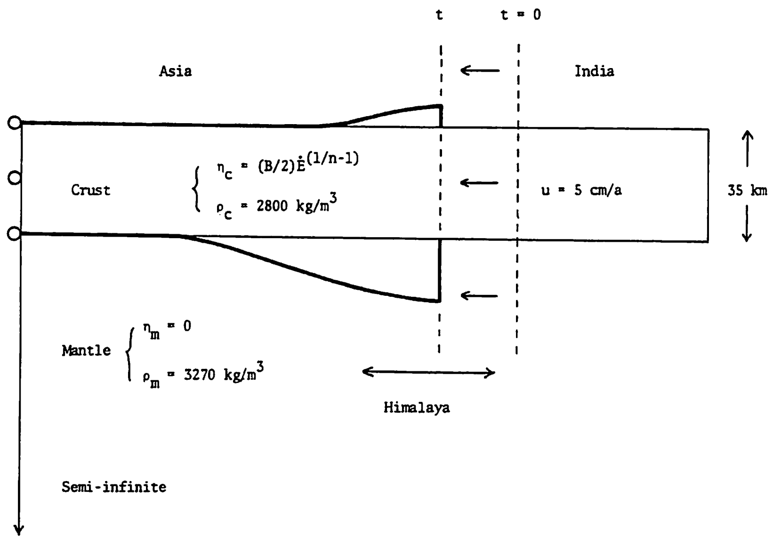



Fig.1 A section of the idealised boundary conditions in England and others' 3 dimensional thin sheet analyses of the Himalaya (England and McKenzie 1982, 1983; England and Houseman 1985, 1986).
B=depth-averaged strength coefficient, E=second invarient of strain rate tensor, n=power law exponent.

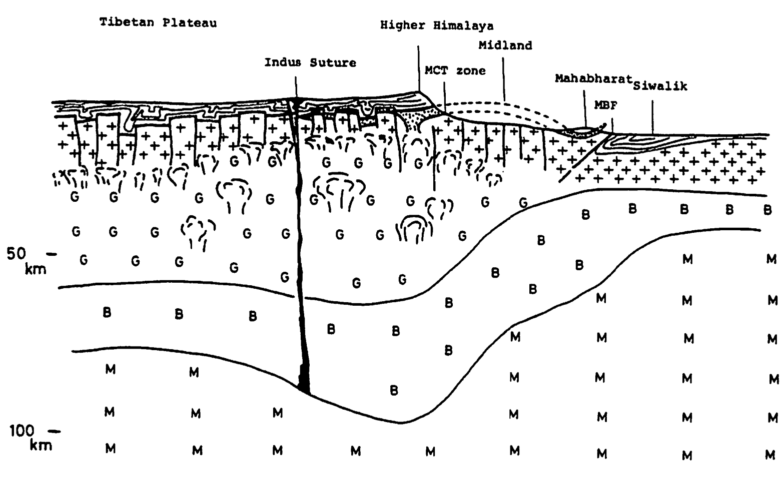



Fig.2 A simplified geological profile of the Himalayas in Nepal (after Hayashi, 1980). Spots=Himalayan Gneiss, Crosses =Precambrian to Palaeozoic basement, G=granitoids with stylised diapirs, B=basaltic layer, M=upper mantle and lower lithosphere.

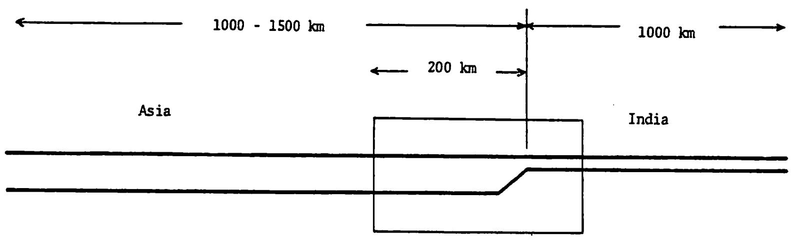



Fig.3a The approximate dimensions of the Himalayan crustal profile, box indicates the analytical area.

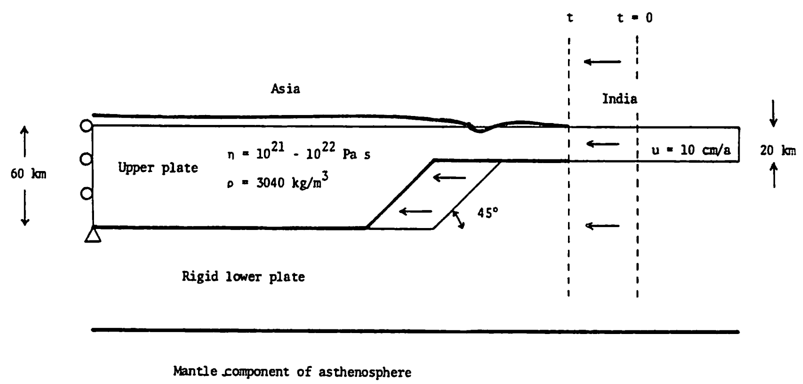



Fig.3b The boundary conditions for our basic progressive distortion model Ii designed to simulate the geology in the area boxed in Fig.3a (see Table 1 for summary of the starting configurations for all six models).

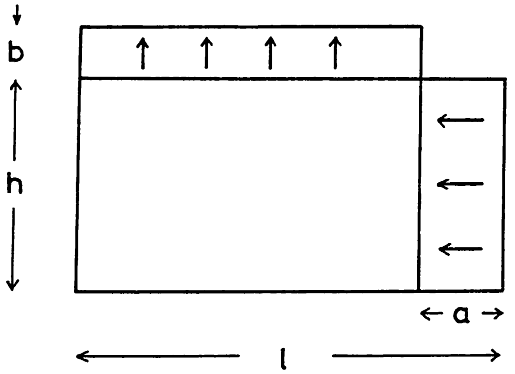



Fig.3c The biaxial strain of a simplified plateau (see text).

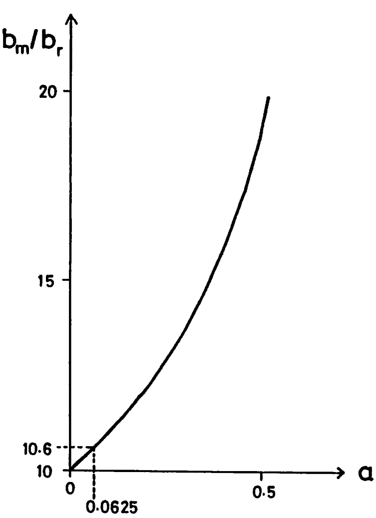
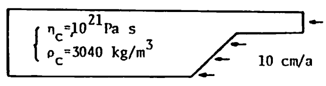
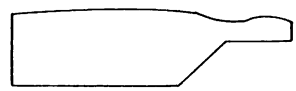
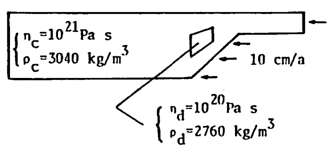
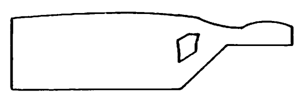
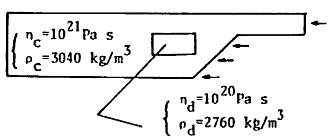
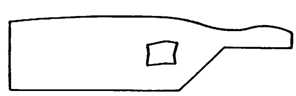



Fig.3d Hyperbola of $b_m/b_r$ (see text).

Table.1 Classification of models.

| | Progressive crustal strain ( 0 - 0.1 Ma ; dt=0.01 Ma ) | Viscous spreading ( 0 - 1 Ma ; dt=0.01 Ma ) |
|---|---|---|
| without diapir | Model Ii   | Model Iii  initial figure=final figure of model Ii |
| with a small diapir | Model IIi   | Model IIii  initial figure=final figure of model IIi |
| with a big diapir | Model IIIi   | Model IIIii  initial figure=final figure of model IIIi |

the relief would spread almost as fast as it forms. We use nodal trajectories to demonstrate that the arcs of progressive and regressive flow are at different levels. We end by suggesting how our model might be improved.

The initial conditions of all six models are summarised on Table 1. Detailed descriptions of the analytical techniques used are given in Hayashi (1979).

## Progressive deformation models

Model Ii (Fig.4): Our fundamental model assumes that a rigid mantle component of the lithosphere plays a significant role in lithospheric plates capped by continent. Fig.4a illustrates the boundary conditions and the elements followed during the northwards advance, at an arbitrary rate of 10 cm/a, of the rigid mantle and its 40 km deep ramp dipping north at 45 degrees (see also Table 1). The viscous crust is divided into 108 isoparametric finite elements with 133 nodal points (Fig.4a). The densities and viscosities of both "India" and "Asia" are first taken as a uniform 3040 kg/m$^3$ and $10^{21}$ Pa s. "India" starts 40 km wide and 20 km thick while "Asia" starts 200 km wide and 60 km thick.

Fig.4b shows the results of deforming our basic model (Ii) by moving the rigid "mantle" 10 km "northwards" at 10 cm/a for 100,000 years. A "Tibetan Plateau" has risen to a general height of 4000 m and the surface of "India" has generally subsided by 500-1000 m. A 3000 m deep foredeep has developed above the ramp which pushed in front of it an "Asia" too viscous to spread as

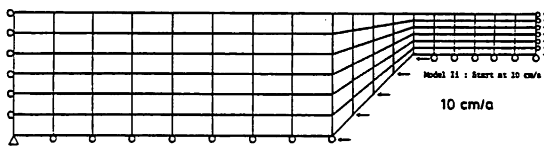



Fig.4a The boundary conditions and parametric elements of our basic model Ii.

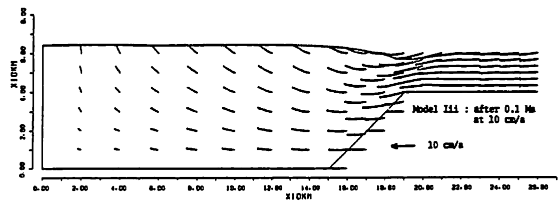



Fig.4b The progressive deformation resulting from moving the mantle in Fig. 4a north at 10 cm/a for 100,000 years. Trajectories followed by each node are indicated.

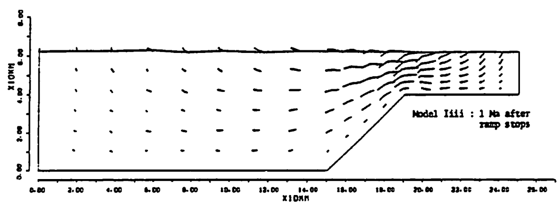



Fig.4c The result after letting the progressively deformed continents in Fig.4b spread because of gravity alone for 1 Ma. Mantle stopped.

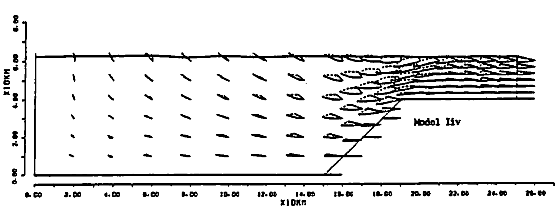



Fig.4d Progressive strain trajectories (solid from Fig.4b) and regressive strain trajectories (dashed from Fig.4c) superposed under the spread relief.

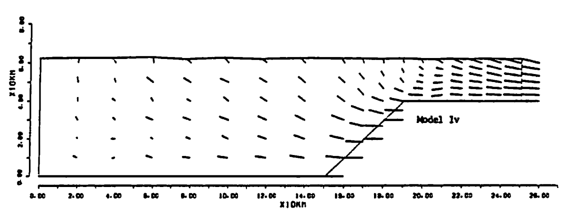



Fig.4e Trajectories of flow constructed by joining the initial and "final" positions of each node in Fig.4d and interpolating.

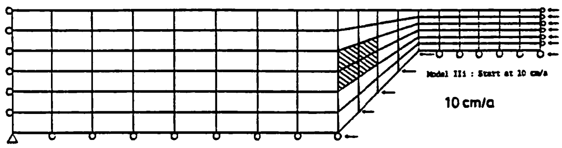



Fig.5a As Fig.4a but with a soft, low-density inclusion above the mantle ramp.

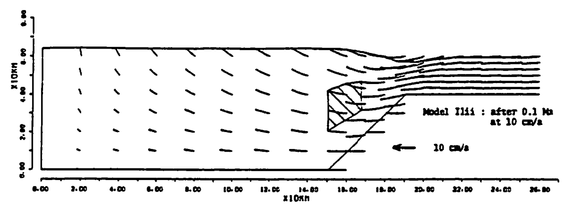


Fig.5b The result after 100,000 years of moving the mantle in Fig.5a north at 10 cm/a. Trajectories followed by each node are indicated.

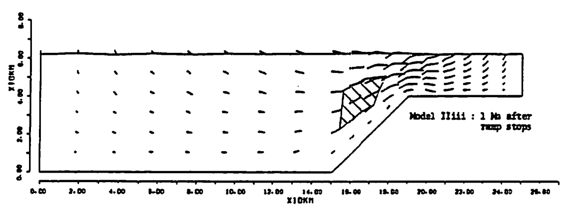


Fig.5c The result after letting the progressively deformed continents in Fig.5b spread because of gravity alone for 1 Ma. Mantle stopped.

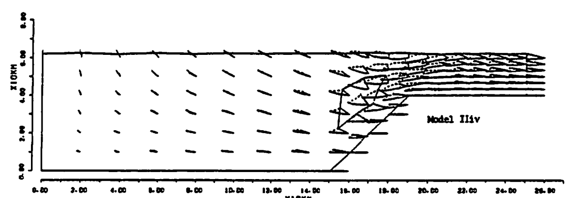


Fig.5d Progressive strain trajectories (solid from Fig.5b) and regressive strain trajectories (dashed from Fig.5c) superposed under the spread relief. The initial and "final" positions of each node are then joined.

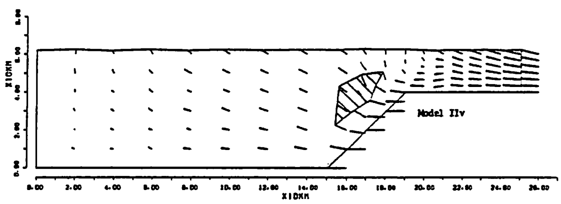


Fig.5e Trajectories of flow constructed by joining the initial and "final" positions of each node in Fig.5d.

fast as it rose.

"India" generally extended but the thinning was inhomogeneously because "India" was too viscous to catch up and fill the foredeep. The result is a maximum surface relief of 7000 m in the "front ranges". Trajectories of the nodes indicate the flow of viscous crust traced a general northerly directed arc down-off "India" (under the foredeep) and up-under the "Tibetan Plateau". This arc is about a centre in the sky, well above the top of the deep rigid-mantle ramp.

Model IIi (Fig.5): In an attempt to take account of the diapirs in Nepal, model Ii was modified to IIi by inserting a soft ($10^{20}$ Pa s), low-density (2760 $kg/m^3$) inclusion in viscous "Asia" above the rigid ramp in the underlying "mantle" (Fig.5b). Only about 300 square km, this soft, low-density inclusion had a negligible effect if model IIi is compared to model Ii (cf. Figs.4b and 5b). The overlying surface rose only locally, and by a few hundreds of m, compared to the rest of the restricted plateau. Inspection of the strain trajectories shows that the differential strain and rise of this inclusion was sufficiently slow that any diapirism (viscous intrusion) was insignificant.

Model IIIi (Fig.6): A larger, 800 square km, inclusion with the same properties was then inserted in "Asia" in front of the rigid mantle ramp (model IIIi,Fig.6a). After 100,000 years of the mantle moving north at 10 cm/a, the differential strain of this inclusion was sufficient to bulge its top about 3 km above its surroundings. The overlying plateau rose in a lower (1 km), wider (100 km), asymmetric bulge simulating the high Himalayan ranges along the southern margin of the Tibetan Plateau. Model IV (Fig.7) indicates that an inclusion of the same dimensions and properties rises about 100 m in 100,000 years in the same crust due to gravity alone. In model IIIi the rise due to gravity is accelerated by the lateral shortening of the soft inclusion. The foredeep in this model was little different from model Ii (Fig.4b) after the same period of progressive deformation.

## Limitations of the boundary conditions in our progressive deformation models

Concentrating the analytical area to the front ranges has the disadvantage of restricting the thickening of "Asia" unnaturally. The confined plateau rises too rapidly. This problem can be qualified using the relationship between the calculated model strains and the crustal viscosity (if this is sufficiently low that the plateau rises with a horizontal top). A simple "$1 \times h$" element of the plateau (Fig.3c) shortening by biaxial pure shear thickens by "b" as it shortens by "a". The assumption of incompressibility results in $b = ha/(1-a)$. The width of the real plateau reaches almost 1600 km, while that in the model is restricted to about 160 km. If the real rise is "$b_r$", and "$b_m$" the model rise is, $b_m/b_r = \{-9/(a-1)\}-1$. The curve of "a" against $b_m/b_r$ is a hyperbola (Fig.3d). Since "a" does not exceed 10 km, $b_m/b_r = 10/160 = 0.0625$, therefore $10 \leqq b_m/b_r \leqq 10.6$. This argument suggests that the uplift of the restricted plateau in all our models is approximately 10 times the uplift of a full-width plateau. In effect, the 0.1 Ma taken for the 160 km wide model plateau to shorten by 10 km would take closer to 1 Ma to rise were it the more appropriate width of 1600 km.

As the thickening of Asia raises a "Tibetan Plateau", isostatic compensation within the viscous crust tends to dissipate the resulting relief. Our unnatural boundary conditions biases the competition between the progressive rise and regressive spreading in favour of the rise. In an attempt to understand and compensate this bias, we isolated the viscous spreading accompanying the shortening by stopping the "northerly" advance of the rigid mantle in each of the three variations of the progressive models to generate three regressive models. Notice that the only isostatic compensation allowed in our all models is confined to the sialic crust.

### Viscous spreading

Any relief in the top free-air surface of a viscous fluid tends to dissipate at a rate

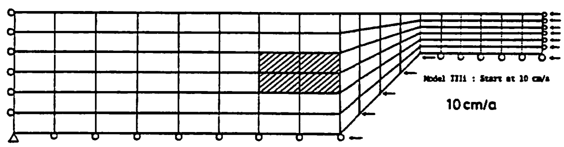



Fig.6a As Fig.4a but with a soft, low-density inclusion in front of the mantle ramp.

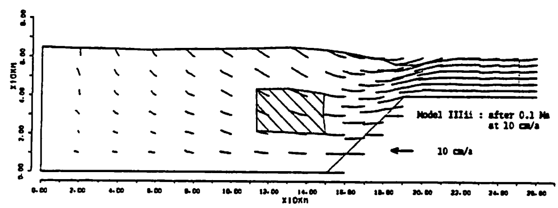



Fig.6b The progressive deformation resulting from moving the mantle in Fig. 6a north at 10 cm/a for 100,000 years. Trajectories followed by each node are indicated.

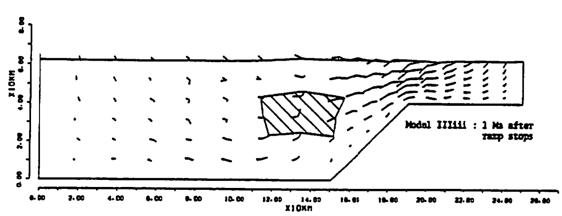



Fig.6c The result after letting the progressively deformed continents in Fig.6b spread because of gravity alone for 1 Ma. Mantle stopped.

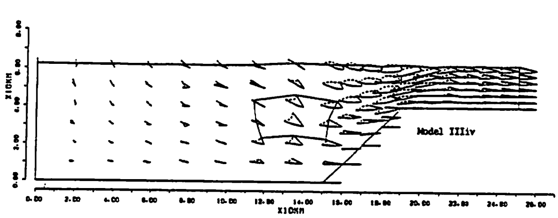



Fig.6d Progressive strain trajectories (solid from Fig.6b) and regressive strain trajectories (dashed from Fig.6c) superposed under the spread relief. The initial and "final" positions of each node are then joined.

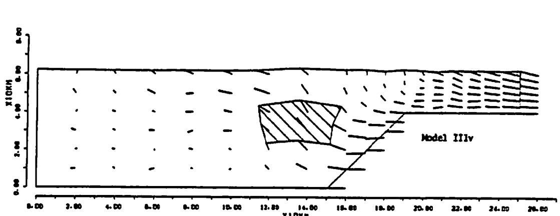



Fig.6e Trajectories of flow constructed by joining the initial and "final" positions of each node in Fig.5d.

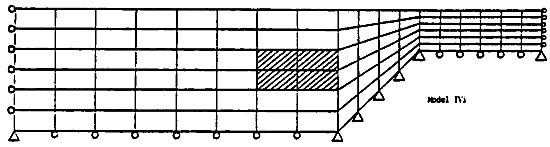


Fig.7a As Fig.6a but mantle stopped so that gravity alone is effective.

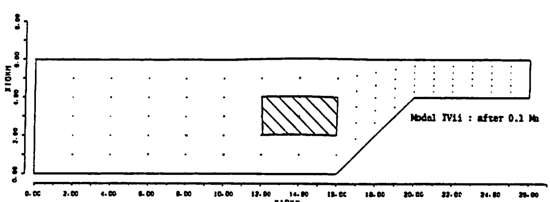


Fig.7b The progressive deformation resulting from only the bouyancy of the soft, low-density inclusion in Fig.7a for 100,000 years. Trajectories followed by each node are indicated.

dependant on the viscosity, relief, gravitational acceleration and time. There is little sign of such spreading in the trajectories of nodes in the progressively deformed models although it must be present (Iii,IIii,IIIii, on Figs.4b,5b and 6b). The restricted plateau shortened so rapidly that its rise all but swamped its spreading. A full-width plateau would have taken about ten times as long to have reached the much the same relief, what would the trajectories have looked like then ? Models Iii, IIii and IIIii, (Figs.4c,5c and 6c) show the effect of stopping the mantle and its ramp (at the stages shown in Figs.4b,5b and 6b) in all three variations of the basic model and letting them spread for a further 1 Ma. The nodal trajectories in model Iiii trace two arcs of flow, one for "Asia" and another for "India", about axes in the sky above both shoulders of the foredeep. Flow in both "continents" fills the foredeep by circulating between the areas of maximum relief and their rigid boundaries. A minor complication is a subsidiary arc up-and-over the top of the rigid ramp in the simplest model (Iiii). Much the same happens in model IIiii (Fig.5b) although the soft, low-density inclusion locally accelerates and steepens the return flow up the ramp and results in a broad "front range" 500 m high. The larger, soft, low-density inclusion in model IIIiii continued to rise through the dissipating plateau and appears to have become diapiric, so that a gentle 1-2 km high "front range" survived the 1 Ma of gravity spreading. Otherwise, the general relief is negligible after about 1 Ma in all three gravity spreading models even in a crust of $10^{21}$ Pa s. These models are the closest our models approached to modelling a Himalayan profile.

Nonetheless, the strain trajectories are sufficiently like those expected for the bulk flow of a pile of crystalline nappes towards "India" to suggest future improvements to the model. Processes of erosion and sedimentation are faster than gravity spreading. If, as seems likely in the real world, the subsiding foredeep had filled with Siwalik-like sediments almost as fast as it subsided, the "crystalline rocks" of the "High Himalaya" would have tended to flow over such infilling sediments, perhaps distorting them to a fold-thrust belt.

## Discussion

Although the limitations of a confined plateau are severe, our simple models reversing the usually considered relative viscosities of the mantle and sialic crust have useful lessons. Our basic model looked promising when minor variations simulated realistic Himalayan profiles. However, because the plateau was restricted so artificially, the progressive shortening and rise of "Asia" was too fast compared to the viscous spreading. "India" actually extended and a foredeep was pulled in the suture zone. These models raise the possibility that "subduction" could be the extrusion and spreading of "Asia" over an extensional foredeep. Nonetheless, stopping the northwards 10 cm/a movement of the rigid mantle ramp after an advance of only 10 km for a period approximately eqivalent to the advance period led to the almost complete dissipation of what had first appeared as a realistic relief.

The restricted-plateau models progressively strained by the mantle moving north at 10 cm/a for 0.1 Ma can be treated as a crude approximation of how a full-width plateau would strain in about 1 Ma. The bulk flow of the viscous "continents" is generally northwards in these models, and then southward when the ramp is stopped for 1 Ma. Regressive flow must have occurred even in the progressive models - but was almost swamped. Stopping the moving "mantle" and letting the relief spread for approximately the eqivalent time was an attempt to redress the bias. At first glance, the fact that the surface relief almost dissipated suggests that the contemporaneous progressive and regressive flows cancelled each other out, but this is not quite so.

Restricting the plateau influences the progressively deforming models (distorted by the deep rigid ramp) far more than the surficial gravity spreading (related more to the surface relief). Figs.4d, 5d and 6d show the nodal displacement trajectories from each pair (moving and stationary) of models superposed. This treatment is obviously crude because the trajectories of northwards flow in the shortening "Asia" (i.e. models Ii,IIi and IIIi) might have been longer and less steep had our restricted plateau been a more realistic width. They also already include an unseen but minor component of gravity spreading. However, given these limitations, the progressive northern flow driven by the deep ramp can be seen in Figs.4d, 5d and 6d to be generally deeper than the regressive surficial spreading.

Figs.4e, 5e and 6e illustrate the trajectories approximating the deformation of a restricted plateau by the rigid "mantle" moving north at 10 cm/a. These trajectories were reconstructed by joining the initial and final locations for each node (dotted in Figs.4d, 5d and 6d) and then interpolating smooth lines. They illustrate that the surficial gravity spreading imposes a regressive return flow on the basic northward rise of the viscous "continental crust". The up-to-the-north arc of flow of "Asia" tends to build a plateau, but there is also an arc of return flow up-and - over the rigid ramp towards "India". In effect, "Asia" begins to extrude back over "India" within only 1 Ma of the collision. Given sufficient time this return flow may generate the nappe pile.

## Future improvements

Future models must be designed so that progressive strains and regressive gravity - spreading occur at equivalent rates.

It is obvious that if our basic models were modified to ensure appropriate rates of both distortion and spreading, much longer than 1 Ma would be needed to generate a Himalayan relief. It is not inconceivable that the Himalayan profile is in a steady dynamic state, spreading driving the nappes as fast as the plateau rises.

From 70-40 Ma India moved north at 15-20 cm/yr relative to Asia. At 40 Ma collision began and the relative closure slowed to about 6 cm/year (Windley 1983) and at leat 470 km of shortening has been proposed for the Pakistan Himalaya (Coward and Butler 1985). However, the closure rate modelled here is an arbitrary 10 cm/year.

Implicit in our (and England and co-workers') models is the notion that the Himalayas are built by "India" advancing northwards faster than "Asia" moves southwards. If, instead, "Asia" advanced south relative to a stationary rigid ramp in our basic model, the flow paths for the rise and dissipation of the relief would have combined: a pile of nappes would move over "India" far more readily. An intermediate situation, of having the rear wall and the ramp approach each other might model nappes extruding over a foredeep.

Further realism might be achieved by changing the dip or height of the mantle ramp in our basic model, slowing the rate of northwards advance of the rigid ramp, advancing the back wall behind "Asia" southwards, infilling the foredeep as fast as it subsides, and moving the initial position of any low-density (+/- soft) inclusion to 120 km north of the top of the ramp.

Having the inclusion both softer and lighter than the surrounding "siallic crust" meant that we could not distinguish the effects of these two properties. A simple low density inclusion rises without lateral shortening because of its bouyancy as in model IV (Fig.7 ; Hayashi, 1979). Lateral shortening may accelerate such a bouyant rise even if the light inclusion was the same viscosity as its surroundings. A soft inclusion can be expected to distort more than its laterally-shortened viscous surroundings and may appear to rise preferentially. The model technique obviously has the potential for clarifying this problem. It could also apply lateral shortening or extension to the gravity-driven overturn of the standard two layer Rayleigh-Taylor instability.

## Acknowledgements

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