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RESEARCH ARTICLE

VISCO-ELASTIC FE MODELING OF CONVERGENT PLATE MARGINS FOR UNDERSTANDING DEFORMATION TOPOLOGY IN TWO DIMENSIONAL

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ABSTRACT

Crustal deformation in vertical direction is higher at convergent plate margins when compared to other plate margins. Even though there are three types of convergent plate margins observed between continental-continental plate, oceanic-continental plate and oceanic-oceanic plate, this study considers only the interaction between oceanic plate and continental plate which are resting on lithospheric mantle to understand the topography effect on continental plate. Two dimensional finite element models are developed and analyzed using commercially available software ABAQUS. Contact properties are defined between plates so that effect of friction is calculated. All plates have an elasto-visco rheology and analysis is carried for 30000 years. The models demonstrate that inclination angles leading to subduction or collision effects the length of vertical deformation profile. Also, increasing the coefficient of friction decreases the vertical deformation but increases the amount of subsidence. This study concludes inclination angle and coefficient of friction plays a vital role for the development of higher topographic regions at convergent plate margins.

INTRODUCTION

The theory of plate tectonics has evolved to be one of the most successful phenomenon's explaining the behaviour of rigid tectonic plates floating around the earth's surface leading to different types of interactions (Convergent, Divergent and Transform). It also explains dynamic evolution of the lithosphere at the plate boundaries (Wilson, 1965). One of the most dramatic and interesting interaction leading to different types of crustal deformations are found where tectonic plates converge. And convergent plate boundaries comprise both subduction and collision zones. At subduction zones geological and geophysical observations suggest that convergence is accommodated by subduction of one plate (oceanic plate) beneath the other (continental or oceanic plate). At collisional plate boundaries the colliding plates are both continental in nature, or one is continental and the other carries a magmatic arc (Schellart and Rawlinson, 2010). In simple the continental convergence (subduction/collision) normally follows the oceanic subduction under the convergent forces of lateral 'ridge push' and/or oceanic 'slab pull' (Turcotte and Schubert, 2002). Geological and other observations show that vertical displacements of the Earth's surface near convergent plate margins may reach magnitudes of the order of hundreds of meters to several kilometers (Westaway, 1993; Doglioni, 1993), few examples for mentioning are the Himalayan–Tibetan belt and the European Alps that are formed by direct continent–continent collision leading to highest peaks, another type where continental collision is highly oblique is at the Southern Alps of New Zealand, and the third different one is arc–continent collision found nearer the belts of Taiwan and the Timor–Banda arc in the southwest Pacific leading to lesser vertical displacements. These displacements may be caused by various processes that are related to plate convergence. For example, the initiation of subduction may induce subsidence of the overriding plate of the order of a few kilometers (Gurnis, 1992), while the termination of subduction will probably lead to uplift (Westaway, 1993; Chatelain *et al.,* 1992). Figure 1 shows the convergent plate margins all over the globe.

Few parameters affecting the evolution of continental collision zones are convergence rate, lithosphere rheology, buoyancy and inter plate pressure (Sobouti and Arkani-Hamed, 2002; *et al.,* Toussaint *et al.,* 2004b). In addition, De Franco (De Franco *et al.,* 2008a; De Franco *et al.,* 2008b) pointed out that the most relevant parameter during the initial stage of continental collision is the geometry and (de)coupling along the plate contact. In that sense the plate contact is in an early stage decisive whether the lithosphere will entirely subduct, delaminate, or will not subduct at all (De Franco *et al.,* 2008a). To obtain subduction Tagawa (Tagawa *et al.,* 2007) suggested

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that weakening of the plate boundary is even more important than the rheology of the lithosphere. Factor that plays a vital role at the contact of two plates is coefficient of friction which makes the interface weak or strong, it also effects the crustal deformation in both horizontal and vertical directions. This study concentrates on crustal deformation during the phase of ongoing convergence between oceanic and continental lying on lithospheric mantle. Major aim of this study is to quantify vertical surface displacements along the plate surfaces resulting from variations in plate geometry, friction, length and boundary conditions.

This study presents three case studies of 2-D numerical models for collision and subduction zone dynamics on a timescale of a few million years, but the time scale is converted into displacement applied to the oceanic plate. All the three plates used for our study are elastic, which leads to the use of an effective thickness. Plates with an effective thickness adequately simulate the surface deformation at a subduction zone (Watts and Talwani, 1974). One of the main advantage of numerical modelling in comparison with all other studies like analogue models, observational models is a larger freedom in choice of material parameters, while stress and topography can be determined at all stages of the experiment.

and Yamato, 2008; Warren *et al.,* 2008a; Li and Gerya, 2009; Li *et al.,* 2010; Li *et al.,* 2011; Li and Ribe, 2012; Li *et al.,* 2012; Duretz *et al.,* 2012; Sizova *et al.,* 2012). Numerical modelling method can be used to (1) testify the conceptual models generated fromnatural observations; (2) investigate the dynamics and mechanism of general continental subduction/collision; (3) study the controls/influences of important physical parameters on the geodynamic processes. The numerical models can be easily applied to investigate the geodynamical problems on variable spatial and temporal scales. Therefore, it is very convenient and can have significant implications for the geological observations.

Based on the widely numerical investigations, the tectonic styles of continental convergence can be summarized into the following six modes: pure shear thickening, folding and buckling, one-sided steep subduction, flat subduction, two sided subduction, and subducting slab break-off (Li *et al.,* 2012). These different modes can be attributed to variable thermo-rheological conditions of the converging plates, as well as the different boundary conditions, etc.

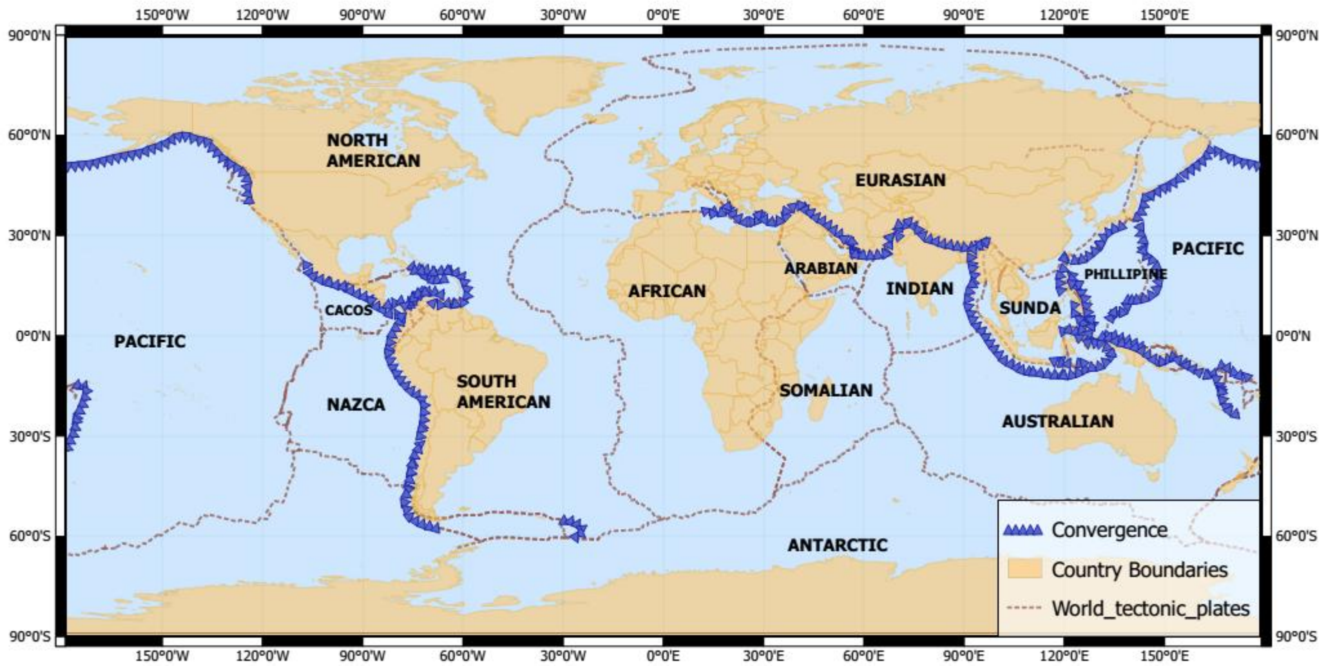

Fig. 1. Convergent plate margins are marked in triangular shape over the tectonic plate boundaries and world political map as represented in legend. (Data: Peter Bird, 2003)

Literature review

The understanding of the dynamics of continental convergent margins implies several different but strictly correlated processes, such as continental deep subduction, HP-UHP metamorphism, exhumation, continental collision, and mountain building. Besides the systematic geological/ geophysical investigations of the continental convergent zones, numerical geodynamic modelling becomes a key and efficient tool (Toussaint *et al.,* 2004b; Beaumont *et al.,* 2001; Burg and Gerya, 2005; Yamato *et al.,* 2007; Yamato *et al.,* 2008; Burov

The role of the plate boundary and its development during continental collision has been studied in both numerical and physical modelling studies (De Franco *et al.,* 2008a; De Franco *et al.,* 2008b; Sokoutis *et al.,* 2005; Willingshofer and Sokoutis, 2009). In most models the plate contact was represented by a predefined weak zone dipping 45° with respect to direction of shortening (De Franco *et al.,* 2008a; Tagawa *et al.,* 2007; Hassani and Jongmans, 1997; Chemenda *et al.,* 2001; Regard *et al.,* 2003; Willingshofer *et al.,* 2005). The implementation of a weak interface separating the upper plate and lower plate with varying thickness, length and angle resulted in different styles of continent collision in terms of orogenic structure and topography.

2-D models are indeed relevant to study the general processes and dynamics in the continental subduction channels and/or the interior of the continental collision zones (Li *et al.,* 2012). This study focuses in the examination of vertical crustal deformation resulting from the oceanic plate colliding with the continental plate with varying angles between them and also the effect of friction at the interface between the two interacting plates in 2-dimensional. Our modelling is similar to other studies (Andrea and Andrain, 2006) carried for geodynamic modelling in terms of materials used and boundary conditions applied.

Numerical study

To understand the effects of collision to subduction on surface displacement near convergent plate margins, 2-D numerical models are modelled on the scale of the whole lithosphere. The mechanical evolution of lithosphere on geological timescales is governed by the equilibrium equation:

$$\nabla.\overline{\overline{\sigma}}+\rho\overline{g}=0 \quad + boundary conditions\ , \qquad (1)$$

Where, $\overline{\overline{\sigma}}$ is the stress tensor, ρ is the mass density and $\overline{g}$ is the gravitational acceleration. This equation is solved using the finite element method based commercially available software ABAQUS/Standard (ABAQUS, 2011), which uses a Lagrangian formulation.

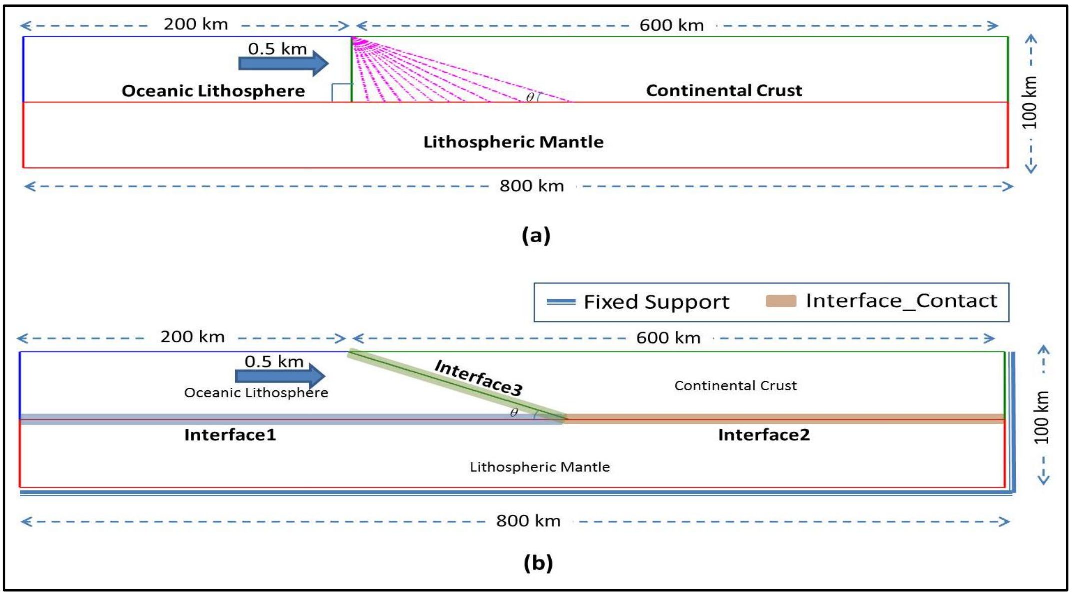

Fig. 2:a. Basic model setup of three plates Oceanic lithosphere, Continental crust and Lithospheric mantle, dotted line with (theta, θ) represents 11 different case studies. b. Model setup indicating contact interfaces (Interface1, Interface2, and Interface3) and boundary conditions

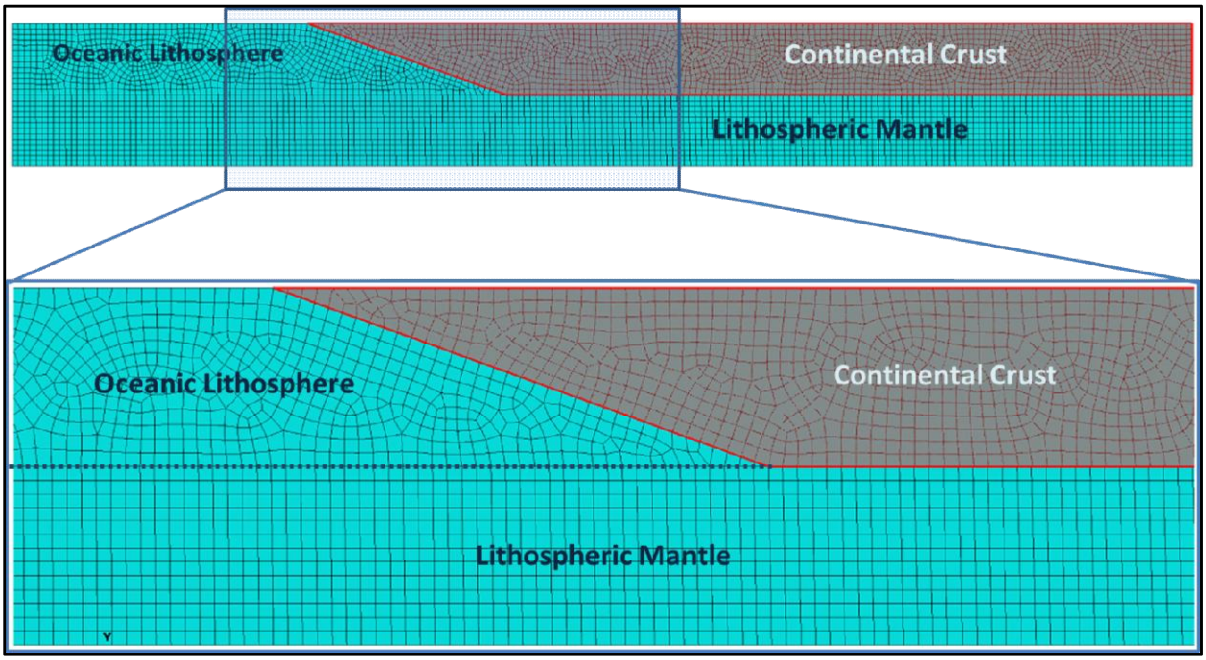

Fig. 3. Finite element grid of the case1, lithospheric mantle plate has equal square elements whereas oceanic and crustal plates have quadrilateral elements because of the inclined plane

This study does not make predictions for any real continental subduction zone, but it focuses on understanding the physical process involved in the transition from collision to subduction. For this reason, generic models based on geometry are considered for analysis, where oceanic plate is collided and subducted underneath of continental plate. In considered models, collisions to subductions zones are represented by 2-D cross sections (Fig. 2-3). Although continental collision process have important 3-D features, the first order effects of convergence can be appreciated by analysing a characteristic cross section normal to trench. With this simplification this study assumes that the continent extends infinitely in the out of plane direction.

The model consists of a 200 km long oceanic plate with a thickness of 50 km, 600 km long continental crust with a thickness of 50 km and a lithospheric mantle of length 800 km with a thickness of 50 km as shown in the Fig. 2. All three plates have an elasto-visco rheology, with a depth-independent Von-Mises yield stress and a temperature-independent linear viscosity. The values of the material properties (cf. Turcott and Schubert 2002; ρ density, E young's modulus, ν Poisson's ratio, η viscosity)are mentioned in Table 2.

tectonic plates, and in step2 displacement of 0.5 km is applied to whole oceanic plate towards continental plate for 30000 years in terms of 1.66 cm/yr velocity. The right end of continental plate, lithospheric mantle and bottom of the lithospheric mantle are fixed throughout the analysis.And the deformation profile is plotted for 3k, 6k, 9k, 12k, 15k, 18k, 21k, 24k, 27k and 30k years (k represents thousand) (Fig-4 to Fig-9) for inclination angles 20^0,25^0,30^0,35^0,40^0,45^0, 50^0,60^0,70^0,80^0 and 90^0. The angle $90^0$is discussed separately as it comes under the pure collision model. All the models are assumed to have no initial stresses developed.

RESULTS

Ten results are presented here in terms of inclination angles mentioned earlier and for each angle five cases based on coefficient of friction are plotted and shown from figures4-9.

Effect of angle

All the numerical studies are analysed for 30000 years to reach 0.5 km of relative slip of oceanic plate on the plate interface1. The whole oceanic plate is moved towards continental plate and different stages of the analysis are performed with μ =0,0.1,0.2,0.3 and 0.4.

Table 1. Contact interfaces properties considered in this study.In this slip means slip is allowed and hard means no gap is allowed once two surfaces are in contact. Only for Interface3 friction coefficient is changed for various inclination angles (20^0, 25^0, 30^0, 35^0, 40^0, 45^0, 50^0, 60^0, 70^0, 80^0 and 90^0)

	Interface1	Interface2	Interface3
Tangential Properties			
a. Contact Type	*slip*	*slip*	*No slip*
b. Friction Coef	μ =0	μ =0	μ =0,0.1,0.2,0.3,0.4
Normal Properties			
a. Contact Type	Hard	Hard	Hard
b. Friction Coef	-	-	-

Table 2. Material properties consideredforthis study. These values are quoted from Turcotte and Schubert 2002; Andrea Hampel and Adrian Pfiffner (2006)

	Continental Crust	Oceanic Lithosphere	Lithospheric Mantle
Density (ρ)	27×10^{11} *kg/km³*	33×10^{11} *kg/km³*	33×10^{11} *kg/km³*
Youngs Modulus (E)	$50 \times 10^{15} N/km^2$	$120 \times 10^{15} N/km^2$	$120 \times 10^{15} N/km^2$
Poissons ratio (υ)	0.25	0.25	0.25
Viscosity (η)	10^{35} Pa S	10^{26} Pa S	10^{25} Pa S

There are three plate interfaces defined in this study (Fig-2b) and are modelled as the contact zone between the separate meshes of the oceanic plate-continental plate, oceanic plate-lithospheric mantle and continental-lithospheric mantle plate. For interface1 slip is allowed as constant velocity is applied to oceanic lithosphere and coefficient of friction is taken as zero,similar properties are also considered for interface 2. For the interface3,the coefficient of friction is increased uniformly from μ =0 to μ =0.4 in the increments of 0.1 to understand the effect of friction. A higher value of the friction coefficient is unrealistic for subduction systems as indicated by heat flow data and palaeo-geothermal gradients of high pressure/low-temperature metamorphic rocks (Molnar Peter and England Philip, 1990). All the elements meshed have an average size of 3 x 3 km for complete model (Fig-3).

In this study, analysis is done in two steps using ABAQUS; In step1, boundary conditions are applied which includes restraints, constraints and contact interfaces between different

The vertical crustal deformation is calculated at intervals of 3000 yrs and plotted against the length of continental plate. Figure 4 shows vertical deformation for angle 20^0 and 25^0. Close observation implies that their exists a point after which the continental plate does not show any vertical deformation. For 20^0 inclination starting 280 km length of continental plate is effected and vertical deformation is uniformly increased with the increase of time interval. For 25^0 inclination starting 244 km length of continental plate is effected and vertical deformation change is also uniform with time interval. It means 5^0 increment in angle has reduced effect on almost 36 km of continental plate when compared to 20^0 inclination angle. But vertical deformation is higher for 25^0 when compared to 20^0. This could be due to change in interface length, as inclination angle increases the interface length decreases for same velocity. So, it is change from subduction to collision. This phenomemnon can be observed for all the results obtained for different inlination angles, i.e between 25^0-30^0, 30^0-35^0, 35^0-40^0, 40^0-45^0, 45^0-50^0, 50^0-60^0,60^0-70^0,70^0-80^0 and80^0-90^0.

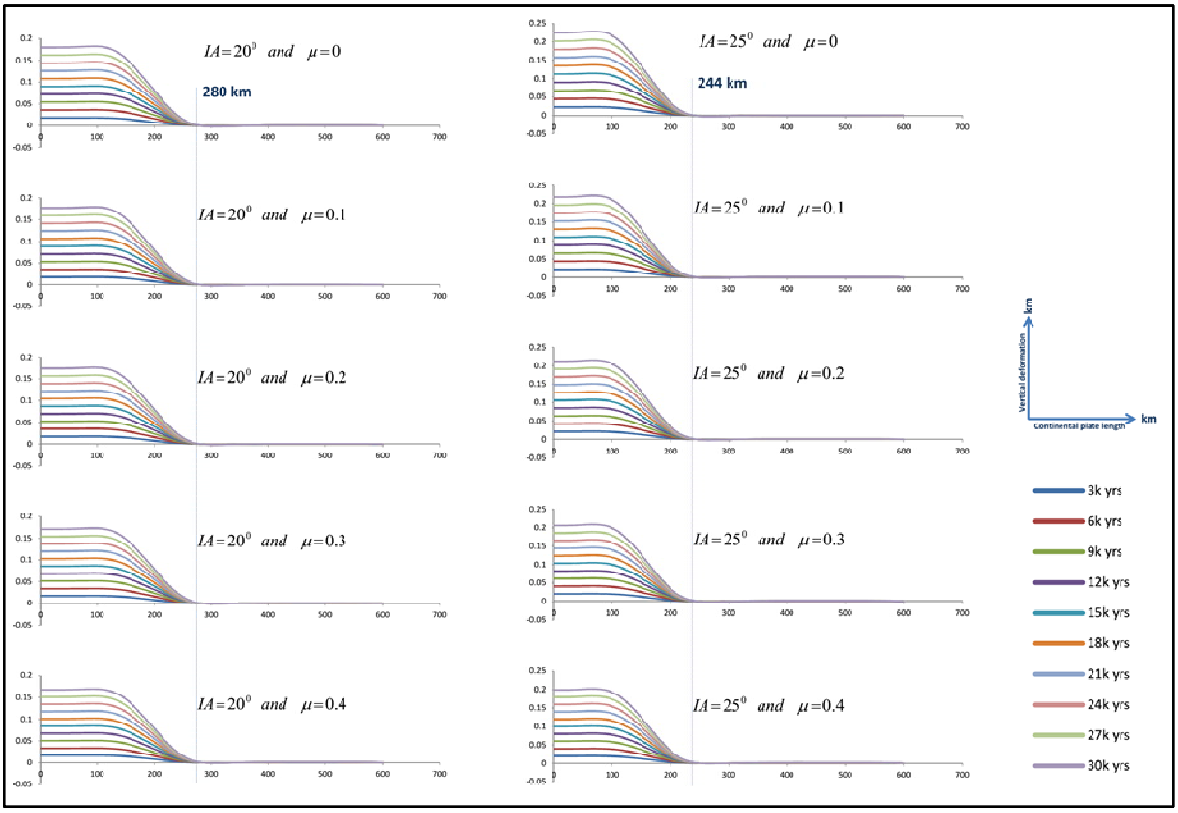

Fig. 4. Finite vertical displacement fields during 0.5 km of slip on the plate interface1 (shown in fig-2.b) for the models 20^0 and 25^0 inclination with uniformly varying coefficient of friction from 0 to 0.4 by 0.1 with the right end of the continental plate fixed. For angle 20^0 common point is at 280 km and for 25^0 angle it is 244 km

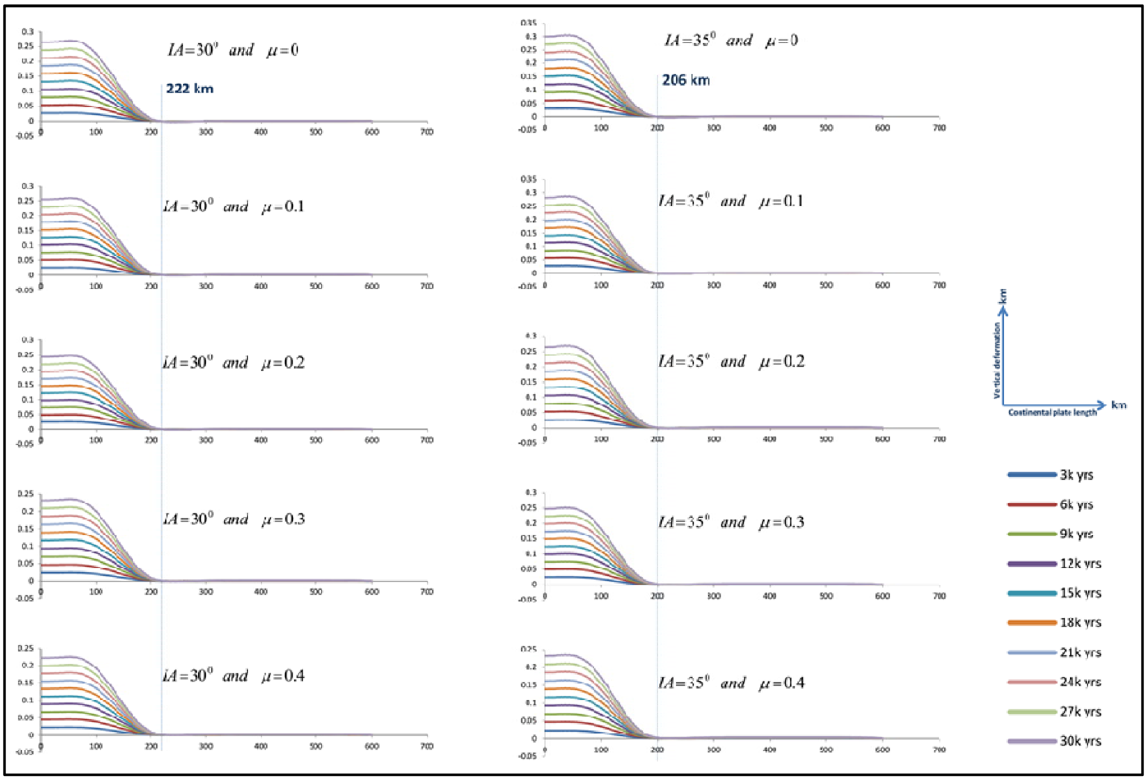

Fig. 5. Finite vertical displacement fields during 0.5 km of slip on the plate interface1 (shown in fig-2.b) for the models 30^0 and 35^0 inclination with uniformly varying coefficient of friction from 0 to 0.4 by 0.1 with the right end of the continental plate fixed. For angle 30^0 common point is at 222 km and for 35^0 angle it is 206 km

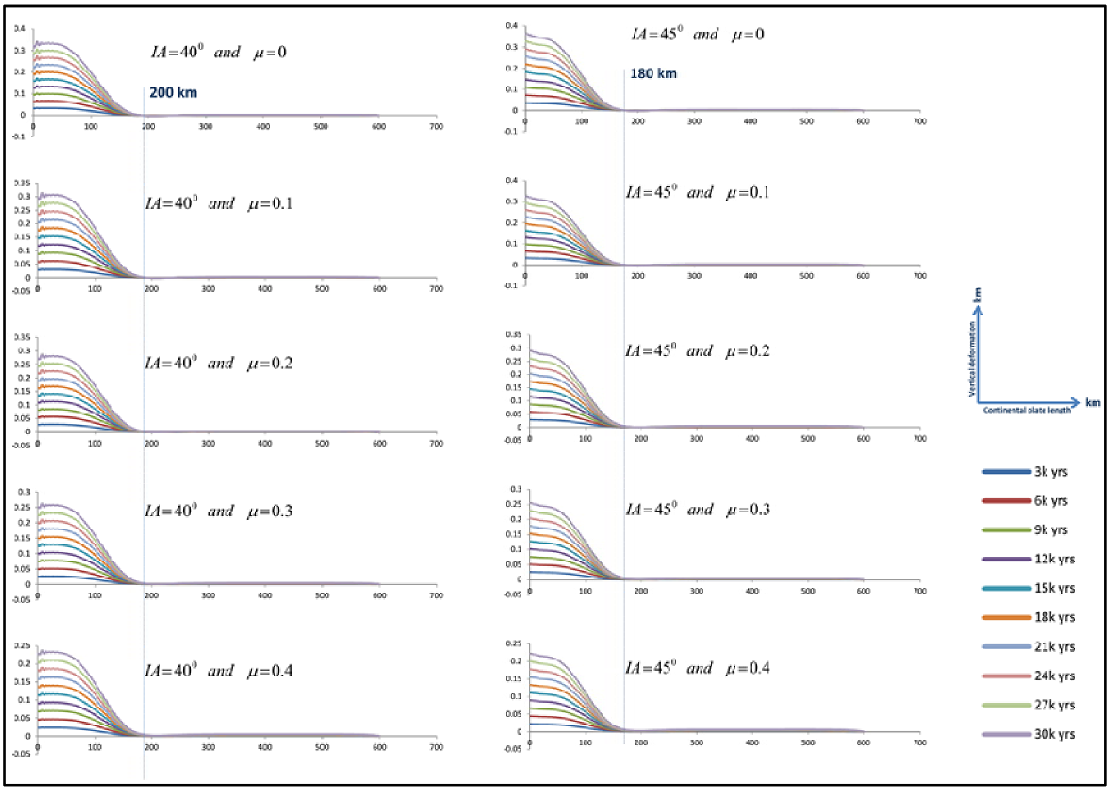

Fig. 6. Finite vertical displacement fields during 0.5 km of slip on the plate interface1 (shown in fig-2.b) for the models 40^0 and 45^0 inclination with uniformly varying coefficient of friction from 0 to 0.4 by 0.1 with the right end of the continental plate fixed. For angle 40^0 common point is at 200 km and for 45^0 angle it is 180 km

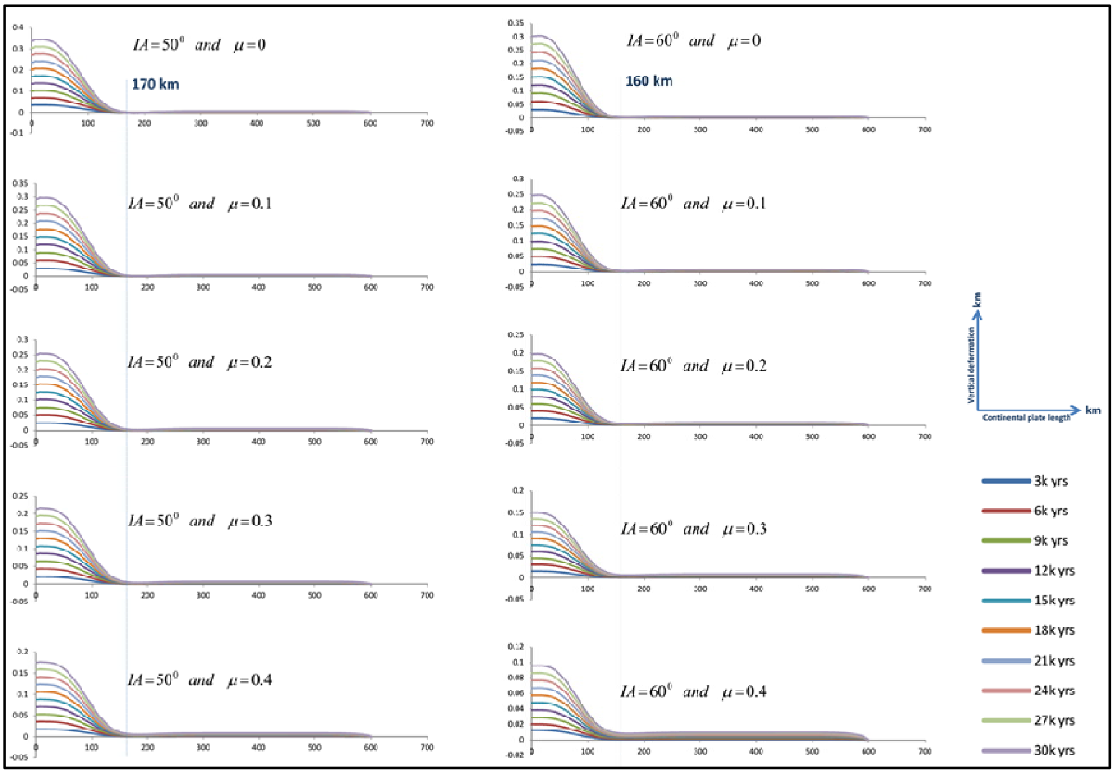

Fig.7. Finite vertical displacement fields during 0.5 km of slip on the plate interface1 (shown in fig-2.b) for the models 50^0 and 60^0 inclination with uniformly varying coefficient of friction from 0 to 0.4 by 0.1 with the right end of the continental plate fixed. For angle 50^0 common point is at 170 km and for 60^0 angle it is 160 km

Figure 5 shows the vertical deformation obtained for inclination angles 30^0 and 35^0, the length of continental plates effected are 222 km and 206 km respectively. Similarly the length of continental crust effected for 40^0 is 200 km and 45^0 is 180 km as shown in the Figure 6. The pattern of vertical deformation in case of inclination angle 45^0 is little different when compared to other inclination angles described earlier. Closer observations reveal that the vertical deformation can be divided into three major regions. Region1 is 0 km to x km (x varies according to inclination angle)of continental plate from left end, where deformation is constant, region 2 is after x km where vertical deformation reduces gradually to 0 and region3, where no vertical deformations are seen. As angle of inclination increases, region1 length decreases but vertical deformation increases. But for inclination angle 45^0, region1 is absent it has region 2 and region 3. And again for 50^0 and 60^0 region1 is seen. In case of 60^0 and μ =0.4, the whole length of the continental plate is effected and this could be due to slow buckling of continental plate. Similar behaviour but higher vertical deformation is seen for 70^0 and 80^0. And more the coefficient of friction more is the buckling effect which are seen in the Figure 7 and Figure 8. For angle 70^0 the effected length is 150 km and for 80^0 it is 130 km. As for 70^0 the region1 explained earlier are not seen. Only region2 is seen where μ =0.3, and whole buckling effect is seen for all five cases of 70^0 and 80^0. The buckling effect is very high and high topographic effect is seen for the angle 80^0 and μ =0.4.

Fig-9(a) shows deformation profile is varying linearly for 30000 years and not much effect of coefficient of friction is seen when compared to other angles. Fig-9(b) is similar to Fig-9(a) comparatively larger difference in vertical deformations is seen. As inclination angle is increased 45^0, slowly the difference in vertical deformation with respective to coefficient of friction are increasing linearly. But from angle 50^0 slowly for μ =0.4, the deformation is not linear any more. This effect is clearly seen for the angles 70^0 and 80^0. Which means apart from the inclination angle, coefficient of friction effect is observed majorly in non-uniform deformation for higher inclinations.

Collision model

This study is separated from other inclination angles since 90^0 is no more an inclination, but it is perfectly normal and this model is also called as perfectly collision model. As oceanic plate is collided with continental plate the whole continental plate is buckled which is shown in the Figure-10(a) and figure-10(b). Figure-10(b) is the zoomed part of first 50 km to see the effect of friction. Even though friction effect is not seen much but a closer observation gives the effect of subsidence for higher coefficient of friction.

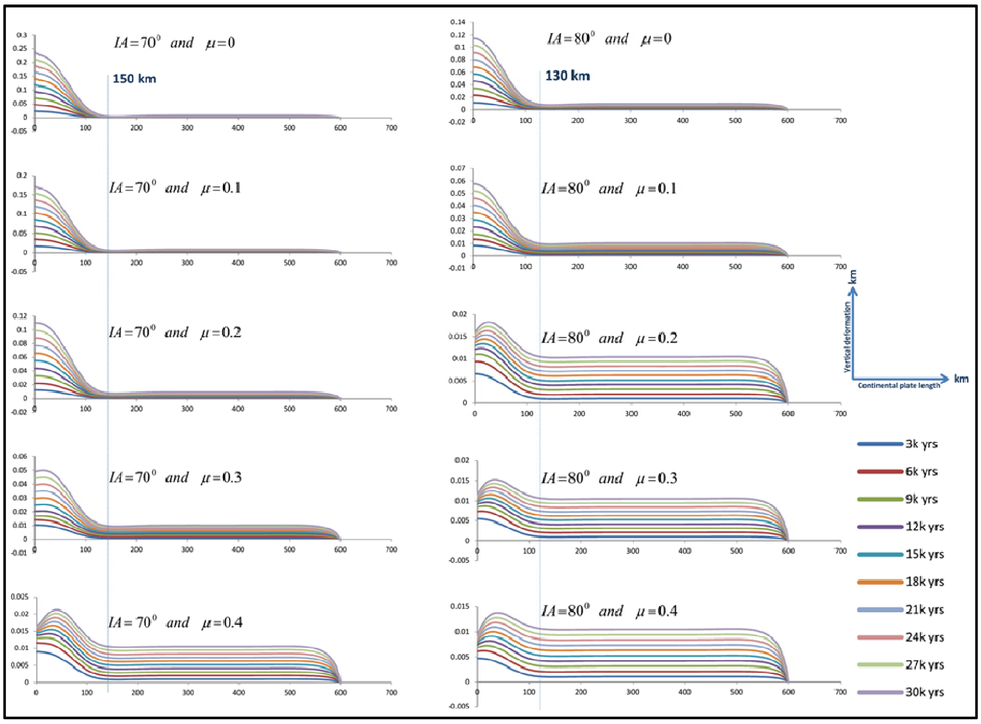

Fig. 8.Finite vertical displacement fields during 0.5 km of slip on the plate interface1 (shown in fig-2.b) for the models 70^0 and 80^0 inclination with uniformly varying coefficient of friction from 0 to 0.4 by 0.1 with the right end of the continental plate fixed. For angle 70^0 common point is at 150 km and for 80^0 angle it is 130 km

Effect of friction

Figure 9 shows the plots plotted between maximum vertical deformation and 30000 years for different coefficient of friction values. This study gives an idea about the effect of coefficient of friction values on various inclination angles.

One of the good examples of this pattern would be collision between Indian tectonic plate and Eurasian plate, where highest peaks are formed and multiple faults are formed MCT (Main Central Thrust), MBT (Main Boundary Thrust) and MFT (Main Frontal Thrust).

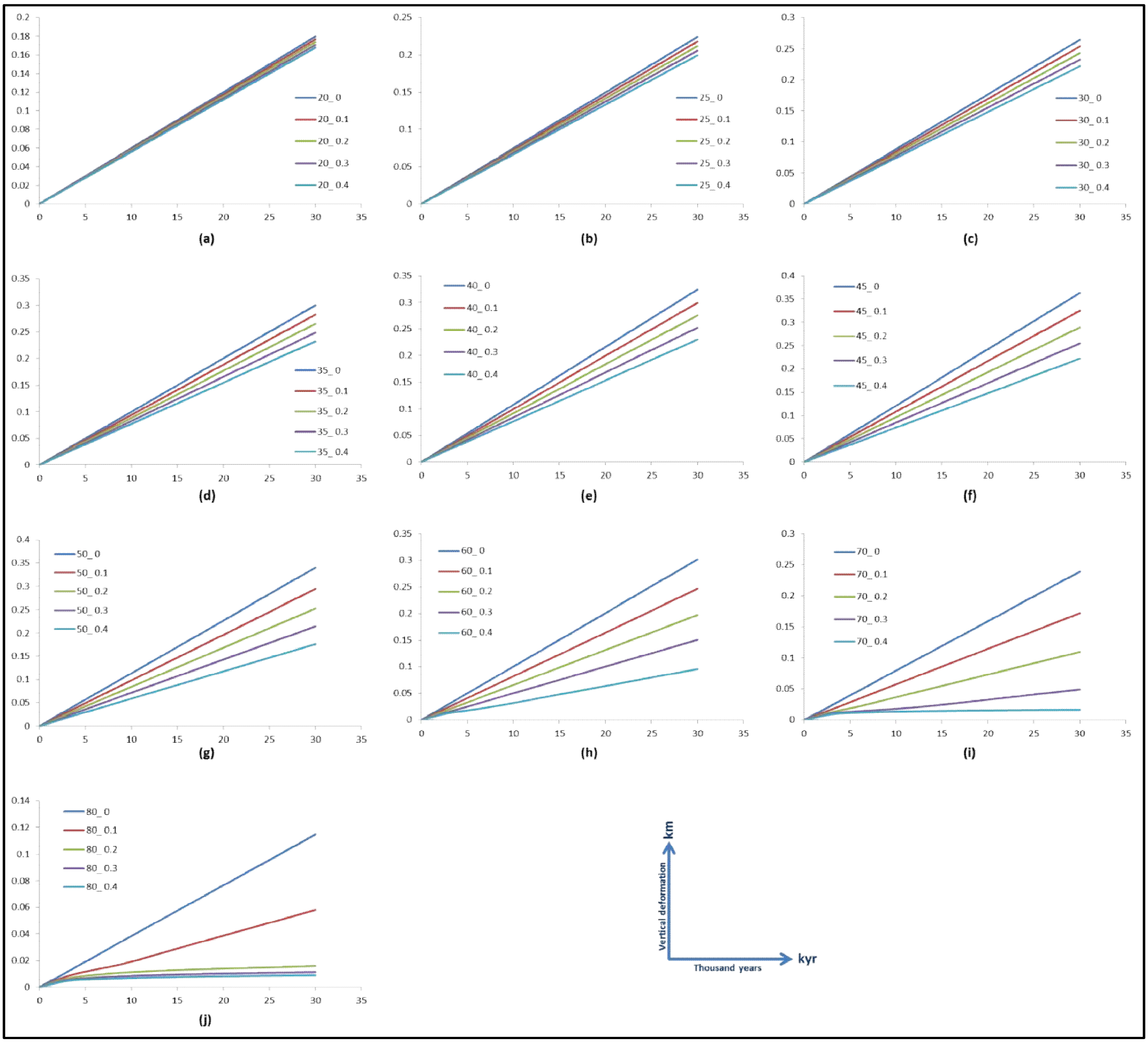

Fig. 9. Maximum vertical displacement obtained for each angle, plotted for 30000 years. Each inclination angle having five cases depending on μ =0,0.1,0.2,0.3 and 0.4

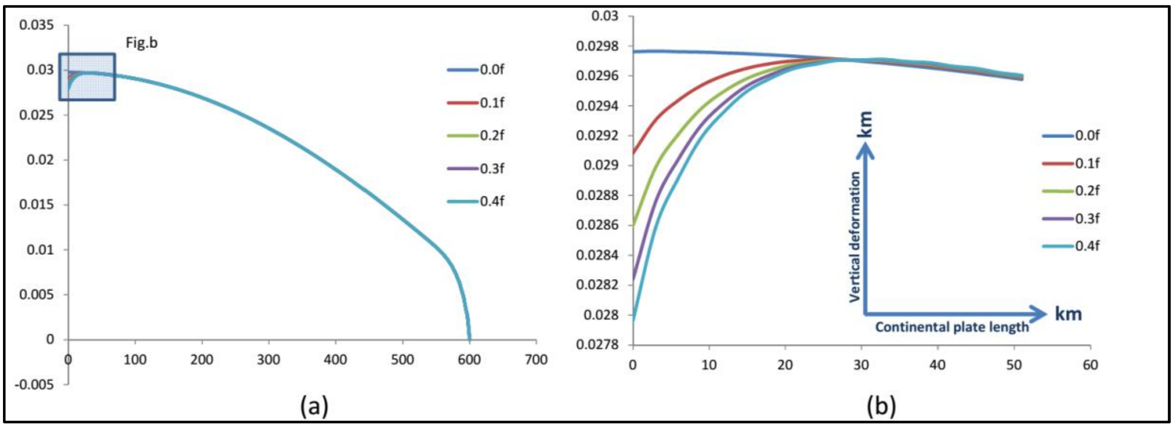

Fig. 10. Vertical deformation of continental plate for complete collision model where angle is 90^0. Interface friction coefficient is increased from 0 to 0.4. b. Enlarged plot as shown in fig.a for starting 50 km of continental plate to know the role of friction coefficient

Conclusion

The results obtained from this study reveal the key role of the geometry of oceanic plate in the formation of topographic evolution at convergent plate margins in terms of inclination angles. And coefficient of friction effect is also clearly seen, as it reduces the vertical deformation but increases the internal stresses in the continental lithosphere. And also leads to the formation of subsidence in the continental plate for higher coefficient of friction. These series of models simulated differently, yet link various tectonic styles.

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