



www.cafetinnova.org

Indexed in
Scopus Compendex and Geobase Elsevier, Chemical
Abstract Services-USA, Geo-Ref Information Services-USA,
List B of Scientific Journals, Poland,
Directory of Research Journals

**International Journal
of Earth Sciences
and Engineering**

April 2015, P.P.106-114

ISSN 0974-5904, Volume 08, No. 02

Horizontal and Vertical Crustal Deformation profiles of a simple Convergent plate margin using Contact Analysis

VENKATA DILIP KUMAR PASUPULETI AND PRADEEP KUMAR RAMANCHARLA
Earthquake Engineering Research Centre, International Institute of Information Technology, Gachibowli,
Hyderabad 500 032, India
Email: dilipkumarpv@research.iit.ac.in, ramancharla@iit.ac.in

Abstract: The process of crustal deformation depends on the type of tectonic plate interactions viz. convergent, divergent and transform. For all the three cases, the topography effect is different. However, higher elevations and huge compressions are measured at convergent plate margins. Past observations reveal that these margins are very much prone to great earthquakes especially at the locations where oceanic plate is subducting underneath a continental plate. For the purpose of understanding horizontal and vertical displacement profiles on both the plates, a study considering the interaction between oceanic and continental plate which are resting on lithosphere mantle is carried out. Two dimensional finite element models were 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 elastic rheology and slip is allowed at the interfaces. The models demonstrate that inclination angles leading to subduction or collision affects the length of vertical and horizontal displacements. Also, increasing the coefficient of friction decreases the vertical deformation but increases the amount of subsidence. This study concludes that the inclination angle and coefficient of friction plays a vital role for the development of varied crustal deformations at convergent plate margins.

Keywords: Convergent plate margins, horizontal and vertical displacements, FEM modeling, contact analysis.

1. Introduction

Global earth is known to consist of three layers, viz., core (inner, outer), mantle (liquid) and crust (solid). Crust, the upper most layers is again subdivided in to huge moving tectonic plates. The theory of plate tectonics has evolved to be one of the most successful phenomenons 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 [1]. One of the most dramatic and interesting interactions leading to different types of crustal deformation are found where tectonic plates converge. Convergent plate boundaries comprise both subduction as well as collision zones. At subduction zones or regions, 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 [2]. 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' [3]. Geological and geophysical 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 kilometres [4, 5]. Few examples for mention 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 might have 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 kilometres [6], while the termination of subduction will probably lead to uplift [4,7]. Figure-1 shows the convergent plate margins all over the globe developed using QGIS.

Few parameters affecting the evolution of continental collision zones are convergence rate, lithosphere rheology, buoyancy and inter plate pressure [8,9]. In addition, De Franco [10,11] 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 decide whether the lithosphere will entirely subduct, delaminate, or will not subduct at all [10]. To obtain subduction, Tagawa [12] suggested 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.

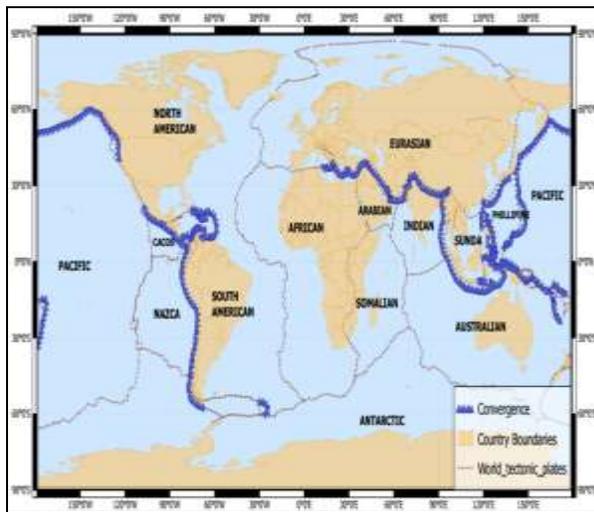


Figure 1: Convergent plate margins are marked in triangular shape over the tectonic plate boundaries and world political map as represented in legend. (Data: Peter Bird, 2003)

This study presents different 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 [13]. One of the main advantages 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.

2. Literature review

The understanding of the dynamics of continental convergent margins imply 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 [9,14-26]. Numerical modelling method can be used to (1) testify the conceptual models generated from natural 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 wide 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 [24]. These different modes can be attributed to variable thermo-rheological conditions of the converging plates, as well as the different boundary conditions. The role of the plate boundary and its development during continental collision has been studied in both numerical and physical modelling studies [10, 11, 27, 28]. In most models the plate contact was represented by a predefined weak zone dipping 45° with respect to direction of shortening [10, 12, 29-32]. 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 [24]. This study focuses in the examination of vertical and horizontal crustal displacements 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. Modelling in this study is similar to other studies [33] carried out for geodynamic modelling in terms of materials used and boundary conditions applied.

3. 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:

$$\nabla \cdot \bar{\sigma} + \bar{\rho} \bar{g} = 0 + \text{boundary conditions} \quad (1)$$

Where, $\bar{\sigma}$ is the stress tensor, ρ is the mass density and \bar{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.

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). 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.

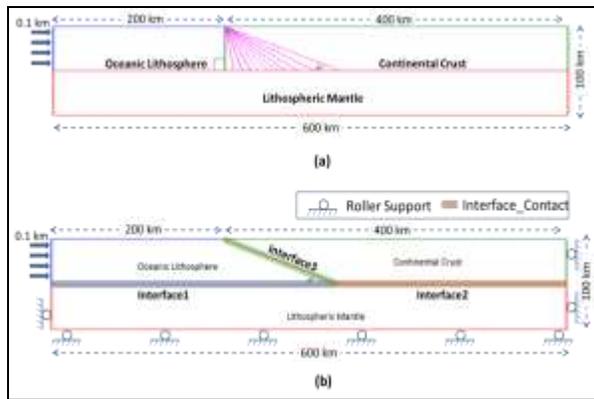


Figure 2: a. Basic model setup of three plates Oceanic lithosphere, Continental crust and Lithospheric mantle, dotted line with (theta, θ) represents 11 different case studies. b. Model setup indicating contact interfaces (Interface1, Interface2, and Interface3) and boundary conditions.

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. Except for 90° for which all three plates are rectangular, remaining for all angles both ocean and continental plates are trapezoidal in geometry resulting in change of contact lengths with different slopes. Contact lengths and coefficient of friction between them play vital role for both stress building as well as crustal deformation. All three plates have an elasto rheology, with a depth-independent Von-Mises yield stress and a temperature-independent linear property. The values of the material properties (cf. Turcott and Schubert 2002;

ρ density, E young's modulus, ν Poisson's ratio) are mentioned in table-1.

Table 1: Material properties considered for this study. These values are quoted from Turcotte and Schubert 2002; Andrea Hampel and Adrian Pfiffner (2006).

	Continental	Oceanic	Lithospheric
ρ	27×10^{11}	33×10^{11}	33×10^{11}
E	50×10^{15}	120×10^{15}	120×10^{15}
ν	0.25	0.25	0.25

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 displacement is applied to oceanic lithosphere and coefficient of friction is taken as 0.4, similar properties are also considered for interface2. For the interface3, the coefficient of friction is increased uniformly from 0 to 0.2 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 [34]. Interface properties for normal and tangential are given in table-2. Under normal property "Hard" means, after the first contact throughout the analysis there will no separation between the interfaces. All the elements meshed have an average size of 3×3 km for complete model (fig-3).

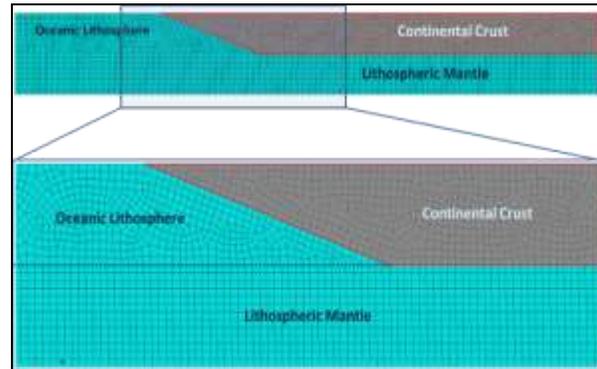


Figure 3: Finite element grid of the case1, lithospheric mantle plate has equal square elements whereas oceanic and crustal plates have quadrilateral elements because of the inclined plane.

Table 2: Contact interfaces properties considered in this study.

Frictional Properties	Interface1 & Interface2	Interface3
Tangential	Slip, $\mu = 0.4$	Slip, $\mu = 0, 0.1, 0.2$
Normal	Hard	Hard

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 tectonic plates, and in step2 displacement of 0.1 km is applied at the end of oceanic plate which is moving towards continental plate. The right end of continental plate, lithospheric mantle and bottom of the lithospheric mantle are supported using rollers throughout the analysis as shown in the figure. And the surface displacement profiles are plotted for different inclination angles 20° , 25° , 30° , 35° , 40° , 45° , 50° , 60° , 70° , 80° and 90° . All the models are assumed to have no initial stresses developed.

4. Mechanism

To detail and discuss results obtained through various numerical simulations carried, a simple free body mechanism is drawn for better explanations of different zonal lengths, which are represented by alphabets. Figure-4(a) represents three interaction interfaces with possible internal forces, fig-4(b) represents displacement is applied at the left end of oceanic lithosphere due to which there would be subsidence of oceanic and upraise of continental at the tip of interaction. So for detailing the zones, the alphabets used are AB, PQ shown in fig-4(c) for surface displacements of Oceanic lithosphere in horizontal and vertical directions. BC, RQ are for horizontal and vertical slips. CC', RR' are the projected contact lengths, whereas C'D and R'S are the length of continental plate describing horizontal and vertical displacements. Fig-4(d) represents free lithospheric mantle plate.

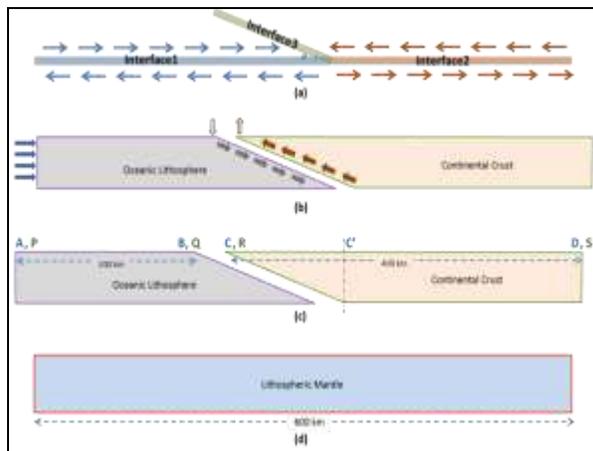


Figure 4: a. Basic model setup of three plates Oceanic lithosphere, Continental crust and Lithospheric mantle, dotted line with (θ , θ) represents 11 different case studies. b. Model setup indicating contact interfaces (Interface1, Interface2, and Interface3) and boundary conditions.

In terms of stress build-up, as slope increases from 20° to 90° , compressive stresses increase in both the tectonic plates and rate of slip decreases. More details are explained in the results obtained.

5. Results

Eleven results with different slopes and for each slope three cases based on coefficient of friction are presented here in terms of horizontal and vertical surface displacements.

5.1. Interaction angle 20°

Considering for horizontal displacements seen from fig-5(a), point 'A' has got horizontal displacement of 0.1 km as it is applied at that node. Length 'AB' has linear decrement of horizontal displacement from 'A' to 'B' as it is going farther from the displacement applied boundary which is quite predictable but the reason for sudden drop at 'B' to 'C' by approximately 0.06 km is due to slip on the interface3, which means point 'B' has moved rightward but point 'C' has not moved, as it can be understood as friction coefficient increases slip decreases by a small amount which can be clearly seen in the figure when $\mu=0.2$ slip is lower than others. If the interface length is projected to horizontal surface its length is 105 km and same can be seen in the region between 'C' and 'C''. Since boundary at point 'D' is restricted in horizontal direction, the horizontal displacement is zero at point 'D'. The same boundary effected linearly between the region 'C' and 'D'.

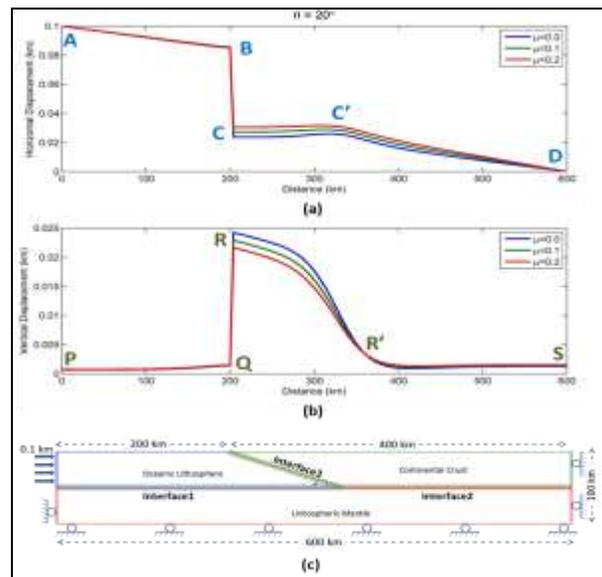


Figure 5: Displacements obtained on tectonic plate surfaces from left end of oceanic to right end of continental when slope angle $\theta=20^{\circ}$ a. Horizontal displacements b. vertical displacements c. Numerical model to show the match for displacements.

Understanding for vertical displacements obtained from fig-5(b), 'PQ' region is almost linear and vertical displacement is almost negligible, this is because of very high subduction. Oceanic plate is smoothly moved underneath of continental plate raising the tip of continental plate which is clearly seen, zone between 'R' and 'Q'. So the highest vertical displacement is seen at the tip of continental plate. At the same time the vertical displacement effect is seen in zone between 'R' and 'R'', which is the effect of interface3 length. And zone between 'R'' and 'S' is almost constant.

5.2. Interaction angle 25°

The results obtained for angle 25° are similar to angle 20°, in case of horizontal displacement the maximum slip 0.055 km. So when compared to previous results the slip has decreased by 0.005 km which also means building of horizontal stress in the tectonic plates. Vertical displacements are almost similar to above results except the effective length of 'RR'' is reduced to 105 km, which is directly proportional to interface3 projection on to horizontal surface.

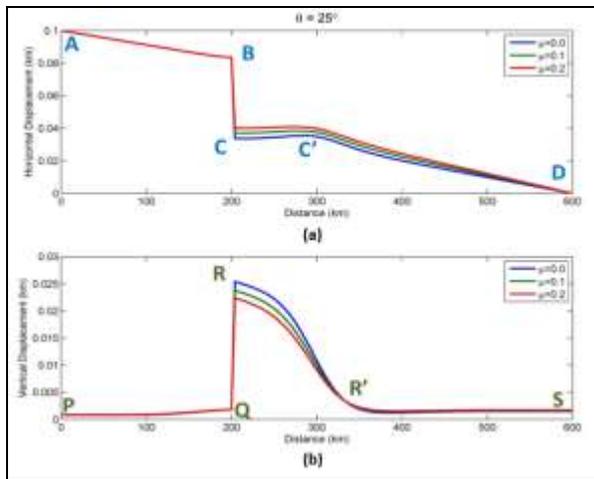


Figure 6: Displacements obtained on tectonic plate surfaces from left end of oceanic to right end of continental when slope angle $\theta=25^\circ$ a. Horizontal displacements b. vertical displacements.

5.3. Interaction angle 30°

The results obtained for slope 30° are also similar to above mentioned cases. Few minor differences found in horizontal displacements as seen in fig-7(a), a minute change from linearity to curvature is seen nearer to the point 'B' and slip is calculated to be approximately 0.04 km. And the length between C and C' is about 85 km. Coming to vertical displacements the maximum displacement obtained is 0.025 km. The small disturbances in the curve are due to mesh sizing, these disturbances can be removed by increasing the fineness of the mesh.

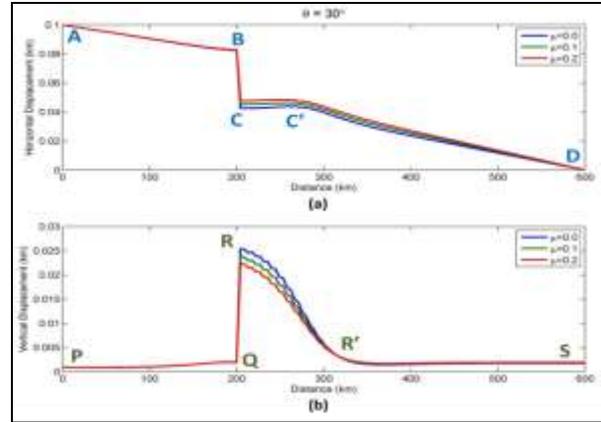


Figure 7: Displacements obtained on tectonic plate surfaces from left end of oceanic to right end of continental when slope angle $\theta=30^\circ$ a. Horizontal displacements b. vertical displacements.

5.4. Interaction angle 35°

These results are also similar above discussed cases, except for the slip and effective length, which are approximately 0.035 km and 70 km respectively

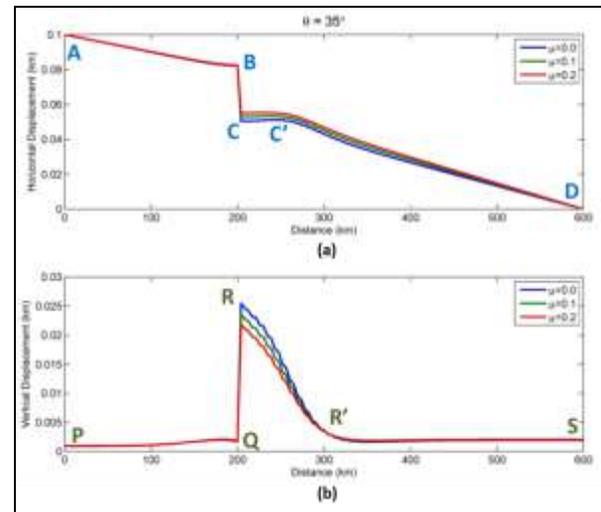


Figure 8: Displacements obtained on tectonic plate surfaces from left end of oceanic to right end of continental when slope angle $\theta=35^\circ$ a. Horizontal displacements b. vertical displacements.

5.5. Interaction angle 40°

In case of 40° the slip is approximately 0.033 km and effective length is 60 km. Small observation reveals the zone between R and R' has slowly transformed from a curvature to linear.

One of the reasons for this change is due to phenomenal change from subduction behaviour to collisional behaviour.

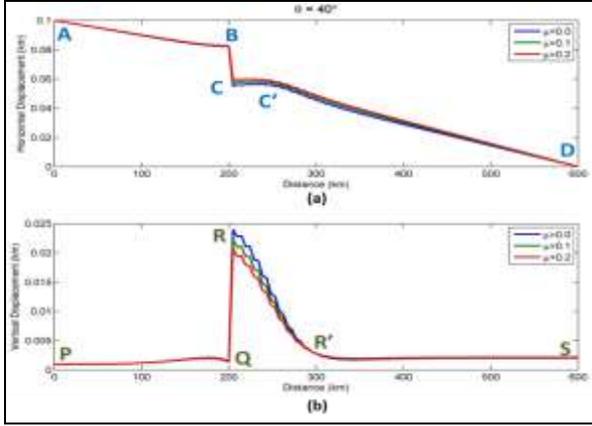


Figure 9: Displacements obtained on tectonic plate surfaces form left end of oceanic to right end of continental when slope angle $\theta=40^\circ$ a. Horizontal displacements b. vertical displacements.

5.6. Interaction angle 45°

The perfect 45° indicate subduction as well as collisional behaviour. The maximum slip 'BC' is approximately 0.023 km and effective length between C and C' is 50 km. As the angle is increasing the slip is decreasing which is seen from horizontal displacements profile. As far as zones between AB and C'C are almost linear.

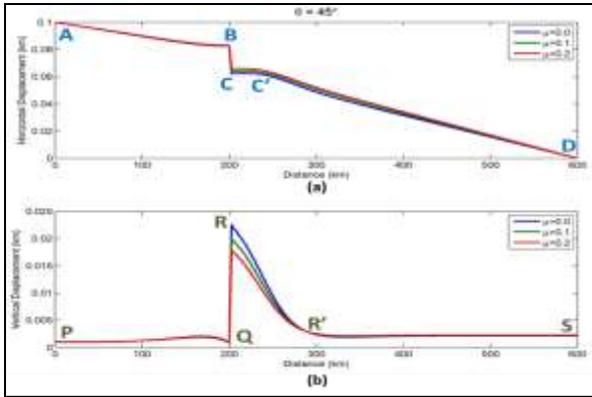


Figure 10: Displacements obtained on tectonic plate surfaces form left end of oceanic to right end of continental when slope angle $\theta=45^\circ$ a. Horizontal displacements b. vertical displacements.

But in case of vertical displacements the region between P and Q is no more linear, resulting in the formation of small rise on oceanic plate nearer to the interaction. Variation is more linear between R and R' when compared to previous cases.

5.7. Interaction angle 50°

The maximum slip is less than 0.02 km and effective length is approximately 40 km, similar description as

above, except point Q which has got zero vertical displacement.

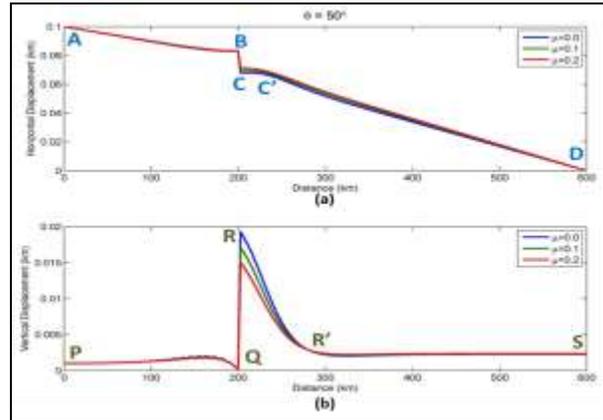


Figure 11: Displacements obtained on tectonic plate surfaces form left end of oceanic to right end of continental when slope angle $\theta=50^\circ$ a. Horizontal displacements b. vertical displacements.

5.8. Interaction angle 60°

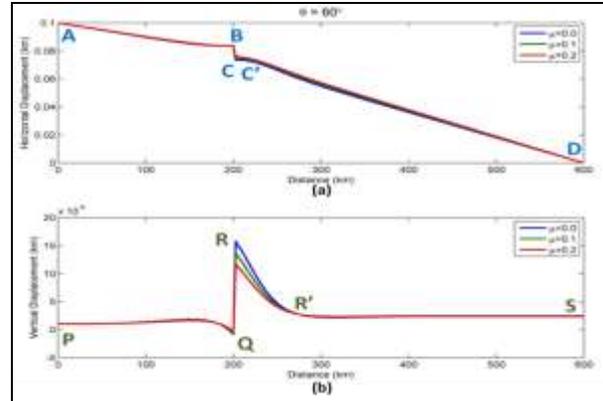


Figure 12: Displacements obtained on tectonic plate surfaces form left end of oceanic to right end of continental when slope angle $\theta=60^\circ$ a. Horizontal displacements b. vertical displacements.

For the angle equal to 60° , the slip is 0.01 km and effective length is 30 km. Unlike previous cases, the horizontal displacement profile has changed in terms of different zones. Even though the reason remains same, more or higher changes are observed in vertical displacements. Slowly as angle has increased the vertical displacement values of R'S zone has increased when compared to zone PQ. This is because of bulge effect in the continental plate which is compressed by oceanic plate.

5.9. Interaction angle 70°

In this case slip is very small and effective length is approximately 20 km. From fig-13(a) it is observed that just before B and just after C, the profile is curved than

the linear, because still the oceanic plate is subducted under continental plate. In vertical displacement profile point Q has gone into negative which means the zone (oceanic plate) has actually subsided, whereas continental tip has slipped and raised by 0.011 km.

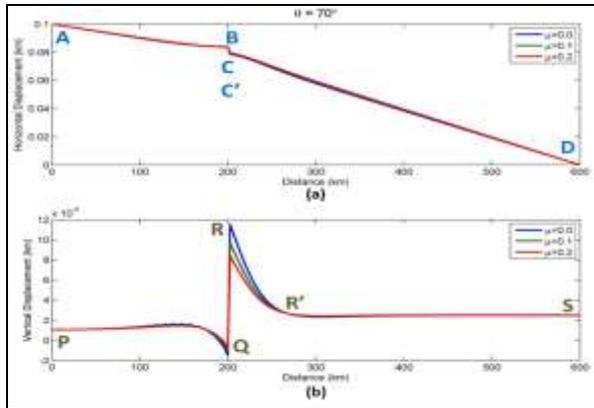


Figure 13: Displacements obtained on tectonic plate surfaces from left end of oceanic to right end of continental when slope angle $\theta=70^\circ$ a. Horizontal displacements b. vertical displacements.

5.10. Interaction angle 80°

The slope of 80° is almost a collisional behaviour, so the horizontal slip is almost zero. The effective length in this case is 10 km. Similar to 70° slope, the oceanic plate has subsided at the point Q but rose between P and Q. Whereas tip of continental plate R has raised by 0.007 km. The elevation effect from R is about 50 km before it becomes constant till point 'S'. Even in this case, vertical displacements are higher on continental plate than oceanic plate. Clear observation shows that there is vertical raise between P and Q, just before it subsides, one of the reason could be the locking of the oceanic plate with continental plate.

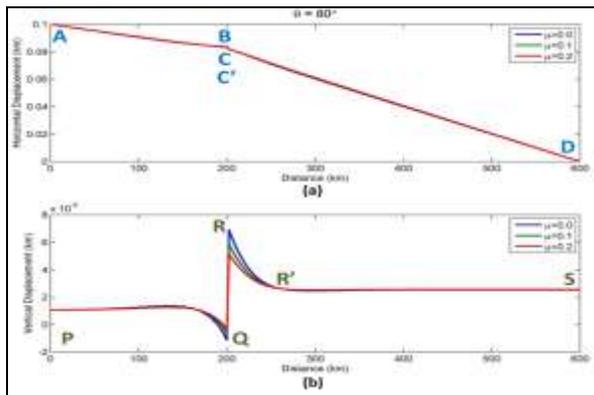


Figure 14: Displacements obtained on tectonic plate surfaces from left end of oceanic to right end of continental when slope angle $\theta=80^\circ$ a. Horizontal displacements b. vertical displacements.

5.11. Interaction angle 90°

In this case slip is zero. Considering for horizontal displacements the slope of AB and CD are different, this has been checked for different lengths of oceanic and continental plates. Only in case of same lengths and same material properties the slope would be equal, as in this case the length of ocean and continental plates vary the slope or horizontal displacements vary with length.

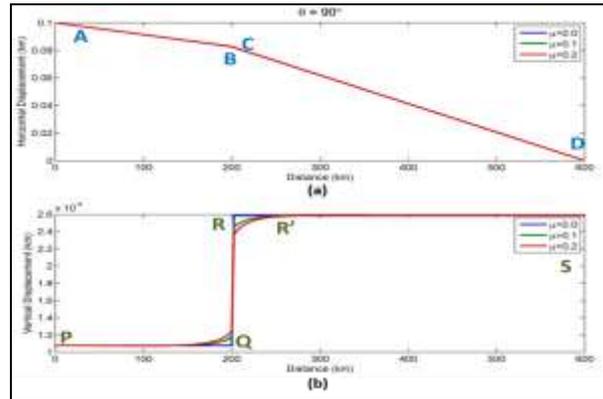


Figure 15: Displacements obtained on tectonic plate surfaces from left end of oceanic to right end of continental when slope angle $\theta=90^\circ$ a. Horizontal displacements b. vertical displacements.

From the vertical displacements figures, the complete continental plate surface has raised, this case is also called complete collisional model. The slip in vertical direction is very less but still the profile shows that it is different for different coefficient of friction values. One of the major reasons for complete raise of continental plate is its material property which is lesser when compared to oceanic plate. This is also seen when a simple numerical simulation is carried out for same material property and same length, the vertical displacements remain same, but for different they are different.

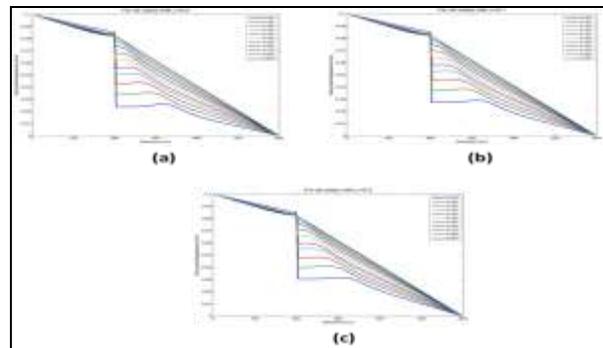


Figure 16: Horizontal displacements obtained on tectonic plate surfaces from left end of oceanic to right end of continental for all the slopes a. $\mu=0$; b. $\mu=0.1$; c. $\mu=0.2$.

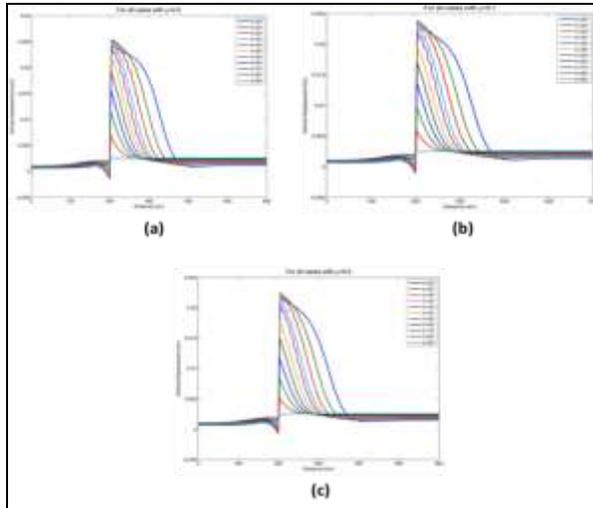


Figure 17: Vertical displacements obtained on tectonic plate surfaces from left end of oceanic to right end of continental for all the slopes a. $\mu = 0$; b. $\mu = 0.1$; c. $\mu = 0.2$.

Figure-16 shows the horizontal displacements for all the eleven cases. Fig-16(a) represents for the coefficient of friction zero, fig-16(b) for the coefficient of friction 0.1, fig-16(c) for the coefficient of friction 0.2. All the horizontal displacement profiles are similar, the maximum drop of horizontal displacements are to 0.022 km, 0.026 km and 0.03 km for coefficient of friction 0, 0.1 and 0.2 respectively.

Figure-17 shows the vertical displacements for all the eleven cases. Fig-17(a) represents for the coefficient of friction zero, fig-17(b) for the coefficient of friction 0.1, fig-17(c) for the coefficient of friction 0.2. All the vertical displacement profiles are similar.

Figure-16 and figure-17 are plotted for general comparison in profile formats.

6. Conclusions

In the paper, a study has been conducted to understand the horizontal and vertical deformations at convergent plate margin using contact analysis. The results obtained from this study reveal that the key role of the geometry of oceanic plate in the formation of topographic evolution at convergent plate margins is in terms of inclination angles. It is also understood that the coefficient of friction influences in reducing vertical deformation and increases the internal stresses in the continental lithosphere. It 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.

This study also, proves to be important in understanding the basic profile changing parameters for both

horizontal and vertical displacements. The results mainly interpreted through slips and effective lengths, which are directly proportional to contact interfaces and friction. Interface3 which was the intersection between oceanic and continental plate played a vital role.

References

- [1] Wilson, J. T., A new class of faults and their bearing on continental drift. *Nature*, 207: 343-347. (1965)
- [2] Schellart, W.P., Rawlinson, N., Convergent plate margin dynamics: New perspectives from structural geology, geophysics and geodynamic modelling. *Tectonophysics* 483, 4–19 (2010)
- [3] Turcotte, D.L. & Schubert, G., *Geodynamics*, Second Edition, Cambridge University Press, United Kingdom (2002)
- [4] Westaway, R., Quaternary uplift of Southern Italy, *J. geophys. Res.*, 98, 21 741–21 772. (1993)
- [5] Doglioni, C., Some remarks on the origin of foredeeps, *Tectonophysics*, 228, 1–20. (1993)
- [6] Gurnis, M., Rapid continental subsidence following the initiation and evolution of subduction, *Science*, 255, 1556–1558. (1992)
- [7] Chatelain, J., Molnar, P., Pre´vot, R. & Isacks, B., Detachment of part of the downgoing slab and uplift of the New Hebrides (Vanuatu) islands, *Geophys. Res. Lett.*, 19, 1507–1510. (1992)
- [8] Sobouti, F., Arkani-Hamed, J., Thermo-mechanical modeling of subduction of continental lithosphere. *Physics of the Earth and Planetary Interiors* 131 (3–4), 185–203. (2002)
- [9] Toussaint, G.; Burov, E. & Jolivet, L. Continental plate collision: Unstable vs. stable slab dynamics. *Geology*, Vol. 32, pp. 33-36 (2004b)
- [10] De Franco, R., Govers, R., Wortel, R., Dynamics of continental collision: influence of the plate contact. *Geophysical Journal International* 174, 1101–1120. (2008a)
- [11] De Franco, R., Govers, R., Wortel, R., Nature of the plate contact and subduction zones diversity. *Earth and Planetary Science Letters* 271 (1–4), 245–253. (2008b)
- [12] Tagawa, M., Nakakuki, T., Kameyama, M., Tajima, F., The role of historydependent rheology in plate boundary lubrication for generating one-sided subduction. *Pure and Applied Geophysics* 164 (5), 879–907. (2007)
- [13] Watts, A.B. & Talwani, M., Gravity anomalies seaward of deepsea trenches and their tectonic implications, *Geophys. J. R. astr. Soc.*, 36, 57–90. (1974)
- [14] Beaumont C, Jamieson R A, Nguyen M H, et al. Himalayan tectonics explained by extrusion of a

- low-viscosity crustal channel coupled to focused surface denudation. *Nature*, 414: 738–742 (2001)
- [15] Burg J P, Gerya T V. The role of viscous heating in Barrovian metamorphism of collisional orogens: Thermomechanical models and application to the Lepontine Dome in the Central Alps. *J Metamorph Geol*, 23: 75–95. (2005)
- [16] Yamato P, Agard P, Burov E., Burial and exhumation in a subduction wedge: Mutual constraints from thermomechanical modeling and natural P-T-t data (Schistes Lustrés, western Alps). *J Geophys Res*, 112: B07410 (2007)
- [17] Yamato P, Burov E, Agard P., HP-UHP exhumation during slow continental subduction: Self-consistent thermodynamically and thermomechanically coupled model with application to the Western Alps. *Earth Planet Sci Lett*, 271: 63–74 (2008)
- [18] Burov E, Yamato P., Continental plate collision, P-T-t-z conditions and unstable vs. stable plate dynamics: Insights from thermo-mechanical modelling. *Lithos*, 103: 178–204 (2008)
- [19] Warren C J, Beaumont C, Jamieson R A., Modelling tectonic styles and ultra-high pressure (UHP) rock exhumation during the transition from oceanic subduction to continental collision. *Earth Planet Sci Lett*, 267: 129–145 (2008a)
- [20] Li Z H, Gerya T V. Polyphase formation and exhumation of high- to ultrahigh-pressure rocks in continental subduction zone: Numerical modeling and application to the Sulu UHP terrane in eastern China. *J Geophys Res*, 114: B09406 (2009)
- [21] Li Z H, Gerya T V, Burg J P., Influence of tectonic overpressure on P-T paths of HP-UHP rocks in continental collision zones: Thermomechanical modeling. *J Metamorph Geol*, 28: 227–247 (2010)
- [22] Li Z H, Xu Z Q, Gerya T V., Flat versus steep subduction: Contrasting modes for the formation and exhumation of high- to ultrahigh-pressure rocks in continental collision zones. *Earth Planet Sci Lett*, 301: 65–77 (2011)
- [23] Li Z H, Ribe N M., Dynamics of free subduction from 3-D Boundary- Element modeling. *J Geophys Res*, 117: B06408 (2012)
- [24] Li Z H, Xu Z Q, Gerya T V., Numerical geodynamic modeling of continental convergent margins. In: Dar I A, ed. *Earth Sciences*. Rijeka: InTech. 273–296 (2012)
- [25] Duret T, Gerya T V, Kaus B., Thermomechanical modeling of slab exhumation. *J Geophys Res*, 117: B08411 (2012)
- [26] Sizova E, Gerya T, Brown M., Exhumation mechanisms of melt-bearing ultrahigh pressure crustal rocks during collision of spontaneously moving plates. *J Metamorph Geol*, 30: 927–955 (2012)
- [27] Sokoutis, D., Burg, J.-P., Bonini, M., Corti, G., Cloetingh, S., Lithospheric-scale structures from the perspective of analogue continental collision. *Tectonophysics* 406 (1–2), 1–15. (2005)
- [28] Willingshofer, E., Sokoutis, D., Decoupling along plate boundaries: key variable controlling the mode of deformation and the geometry of collision mountain belts. *Geology* 37 (1), 39–42 (2009)
- [29] Hassani, R., Jongmans, D., 1997. Study of plate deformation and stress in subduction processes using two-dimensional numerical models. *Journal of Geophysical Research* 102 (B8), 951–965. (1997)
- [30] Chemenda, A.I., Yang, R.K., Stephan, J.F., Konstantinovskaya, E.A., Ivanov, G.M., New results from physical modelling of arc-continent collision in Taiwan: evolutionary model. *Tectonophysics* 333 (1–2), 159–178 (2001)
- [31] Regard, V., Faccenna, C., Martinod, J., Bellier, O., Thomas, J.-C., From subduction to collision: control of deep processes on the evolution of convergent plate boundary. *Journal of Geophysical Research* 108. (2003)
- [32] Willingshofer, E., Sokoutis, D., Burg, J.-P., Lithospheric-scale analogue modelling of collision zones with a pre-existing weak zone. *Geological Society, London, Special Publications* 243 (1), 277–294 (2005)
- [33] Andrea H and Andrain P., Relative importance of trenchward upper plate motion and friction along the plate interface for the topographic evolution of subduction-related mountain belts. Buiters, SJH and Schreurs, G. *Analogue and numerical modelling of crustal-scale processes*. Geological society, London, Special publications, 253, 105–115 (2006)
- [34] Molnar Peter and England Philip, Late cenozoic uplift of mountain ranges and global climate change: Chicken or egg ?, *Nature*, Vol.349, 29–34 (1990)