Discrete element modeling of continental deformation and volcanic spine extrusion

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**DISCRETE ELEMENT MODELING OF
CONTINENTAL DEFORMATION AND
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Summary

Understanding the discontinuous nucleation, growth, and interaction of large faults within continental collision zones remains a challenge. The India-Asia collision zone is an example of the largest present-day continental deformation, which started about 55 million years ago. The collision triggered large strike-slip faulting horizontally, and generated the broadest Tibetan plateau vertically. Previous analog experiments simulating the India-Asia collision successfully modeled the development and kinematics of large strike-slip faults within the Eurasian plate. However, these 2D experiments were dynamically unscaled with gravity and did not allow the development of topographic relief.

Here, we use the YADE Discrete Element Method (DEM) code to produce a suite of 3D models. These 3D DEM models simulate two plate-boundary size strike-slip faults that extrude and rotate coherent plate-size blocks. The model locations, lengths, ages and offsets of these faults are in general consistency with those of the Red River and Altyn Tagh mega-faults. The former fault in the model is observed to change sense after the activation of the latter, as was the case for the Red River fault. This is the first time any type of model or simulation of the collision reproduces such a fundamental geological change. As in the Asian collision zone, the deformation of the model is observed to be fully 3D. Coevally with strike-slip movement, large scale thrust faults generate the progressive growth, from south to north, of plateaus. This is in general agreement with the

stepwise, northwards rise of the Tibet-Qinghai plateau. Finally, we analyze the shortening amounts accommodated by vertical and horizontal deformation respectively. Our model results are broadly consistent with the observed topographic, tectonic and geological evolution of Eastern Asia in the last ~50 million years.

Volcanic seismicity is common before and during silicic eruptions. Repetitive seismic events often occur at roughly constant depth, in swarms, beneath actively extruding domes or spines. They typically involve periodic excitation by repeatable sources. Understanding the mechanism of such seismicity is important for hazard assessment. The observed stationary position of the sources, and their relationship with degassing are difficult to explain by faulting of cold host rocks surrounding ascending magma. Slip along the conduit walls accounts partly for gas ring escape around the crater rims, but not for seismicity at fixed depth. The existence of brittle-ductile fault textures in silicic lavas indicates that fracturing/faulting occurs within the magma itself, but studies at Montserrat and Mt St Helens suggest this takes place only in a transitional shear zone between hot magma and cold host rock near the conduit wall. Hence, such faulting would also be uniformly distributed along that wall. One way to account for hypocenters located at a fixed depth is to invoke geometrical changes along the conduit. Here, we analyzed the focal mechanisms of volcanic seismicity at Mount St. Helens during the 2004-2006 eruptions. Volcanic earthquakes fault-plane solutions associated with the extrusion of spines during that eruption support the occurrence of a new mechanism, coevally with shear along the conduit walls. Dominant thrust fault-plane solutions may be interpreted to imply

constriction of the ascending magma as it is squeezed past a neck in the conduit. We use a Discrete Element approach also based on the YADE code, with general material parameters leading to fault nucleation, to simulate the stress field and the growth and evolution of faults inside a neck at fixed depth in the conduit. The birth of open cracks in a “secondary tension” zone at the center of the spine also suggest a very efficient mechanism (fracking) for the extraction of gas from inside the magma, accounting for the remarkable, though poorly understood, low explosivity of silicic spine eruptions.

Chapter 1 Introduction

Modelling deformation that includes faulting in tectonics and volcanology still remains a challenge. A typical and widely used technique is the finite element approach, but it is only adapted to continuous, bulk deformation or, at most, to motion on faults that is artificially introduced in models at the initial stage. For simulation of faulting, a more advanced approach is the Discrete Element Method (DEM). Here we use this method to address two long-standing issues: simulation of both large-scale faulting and crustal thickening within continental plates and, at a smaller scale, seismic faulting during volcanic eruptions.

In the case of large-scale continental plates, the finite element method (FEM) has remained the typical approach (England and Houseman, 1986; Houseman and England, 1986; Cook and Royden, 2008). This method can produce an average deformation field in 3D, including both thickening or thinning as well as, more artificially along pre-introduced interfaces, horizontal shear. However, it cannot generate fault nucleation, propagation, and localization of shear within initially homogeneous and continuous materials.

Another challenging problem is the modeling of stationary seismicity during volcanic eruptions. Volcanic eruptions involving fluid magma ascent, transport and escape may be modeled using the FEM. But earthquakes inside volcanic edifices cannot occur in fluids and thus cannot be fully understood with that technique. Typical volcanic earthquakes during seismic eruption, which are

located at steady depths, are well documented instrumentally, but not fully understood.

Here, we investigate the potential value of the discrete element method to illuminate these two geological problems at very different scales.

1.1 Continental Deformation

Continental deformation, typically the Asian deformation related to the India-Asia collision zone, has been simulated for decades. The deformation of the Asian plate is characterized by large-scale strike-slip faults and the highest and broadest plateau in the world. The deformation thus involves both horizontal shortening and vertical thickening. Two particularly large strike-slip faults, the Red River and Altyn Tagh faults, have absorbed part of the collision shortening by horizontally lateral motions (extrusion). The other part, crustal thickening, is consumed by mountain building. Much of the crust has been thickened vertically to form the Himalayas and the Tibetan Plateau. The Tibetan Plateau is the broadest region of high elevation (>4500 m high, e.g. (Fielding et al., 1994)) in the world with the thickest crust (>70 km thick; e.g. (Wittlinger et al., 2004)) (Fig. 1.1). It is bounded by the Himalayan range in the south, the Kunlun and Qilian Shan Mountains along the Altyn Tagh and Haiyuan faults in the north, and the Long Men Shan range in the east. The Tibetan Plateau is composed of three sub-plateaus: Eocene Tibet (Lassa block), Oligo-Miocene Tibet (Qiangtang block), and Plio-Quaternary Tibet (Tsaidam block), that appear to have grown stepwise from south to north since the Early Cenozoic (Meyer et al., 1998; Tapponnier et al., 2001; Vergne et al., 2002; Liu-Zeng et al., 2008). The Plio-Quaternary Tibet is

bounded by the Altyn Tagh, Qilian Shan, Haiyuan fault and Kunlun fault, the Oligo-Miocene Tibet is surrounded by the Kunlun Shan, Long Men Shan, Xianshuihe fault, Tanggula Shan and Altyn Tagh fault, and the Eocene Tibet is mostly banded by the Tanggula and Gangdise Shan (Fig. 1.2).

Fig. 1.1. GPS velocities (Kreemer et al., 2014) in and around the Qinghai-Tibet plateaus show present day active movements at the center of the India-Asia collision zone.

Fig. 1.2. Stepwise growth of Tibet: the Tibetan plateau is made up of several sub-plateaus separated by distinct boundary ranges that rose successively northwards at different periods (Tapponnier et al., 2001).

Interpretations of the Asian plate deformation range from the early strike-slip extrusion model (Tapponnier and Molnar, 1977; Tapponnier et al., 1982, 1986; Peltzer, 1988; Peltzer and Tapponnier, 1988a) to the 3D stepwise growth model (Meyer et al., 1998; Tapponnier et al., 2001; Wittlinger et al., 2004; Liu-Zeng et al., 2008). The analog indentation model (Fig. 1.3), showed how strike-slip faulting north of the Himalayas is associated with sideways extrusion of two continental blocks or sub-plates. A number of geological and geophysical observations have provided considerable evidence for large offset along the two strike-slip faults bounding these two blocks and for their lithospheric extent (Peltzer et al., 1989; Tapponnier et al., 1990a, 1990b; Avouac et al., 1993; Leloup

et al., 1993; Gaudemer et al., 1995; Leloup et al., 1995, 2001; Armijo et al., 1996; Lacassin et al., 1997, 1998; Wittlinger et al., 1998; Replumaz et al., 2001; Mériaux et al., 2004). The stepwise development of the plateau (Meyer et al., 1998; Tapponnier et al., 2001) appears to be correlated with the development of internal drainage (Liu-Zeng et al., 2008). The various new datasets and research results on the faults were incorporated into block model reconstructions of Asian deformation (Replumaz and Tapponnier, 2003; Replumaz et al., 2004, 2010). This stepwise growth model of the Tibetan plateau, which combines the effects of strike-slip and thrust faulting and hidden mantle subduction beneath Tibet is in the process of being tested by seismic studies (Vergne et al., 2002, 2003; Wittlinger et al., 2004; Xu et al., 2009; Mechie et al., 2011; Mechie et al., 2012).

Fig. 1.3. Plasticine analogue model reproducing major strike-slip faults, opening of the South China Sea, and Sundaland block rotation (Peltzer and Tapponnier, 1988b).

In general, models of the deformation history of the Tibetan Plateau can be separated into four main types.

(1) Argand wholesale underthrusting: complete underthrusting of Tibet by India

According to that model, the thick crust of Tibet formed as the entire plateau was underthrust by continental Indian (Argand, 1924). This model focused on explaining the about doubled thickness of the Tibetan crust and the uniform surface elevation/uplift across the plateau. This idea, and its general consequences, are still advocated today on the basis of the topographic results of projects such as the International Deep Profiling of Tibet and the Himalaya (INDEPTH) and other Himalayan/South Tibetan tomographic studies [e.g. (Nelson et al., 1996)] (Fig. 1.4).

Fig. 1.4. Cross-section of Argand wholesale underthrusting model (Nelson et al., 1996)

(2) Whole lithosphere thickening model

In general, this model proposes that Tibetan deformation can be described in terms of a soft lithosphere continuously shortened and thickened by northward push along its southern boundary. Thickening is modulated by gravitational lateral flow towards the edges of the plateau. (Fig. 1.5) (England and Houseman, 1986; Houseman and England, 1986; England and Molnar, 1997). No horizontal decoupling (including by décollement thrusting) is allowed, particularly at the crust/lithospheric mantle boundary, in marked contrast with the general

understanding of deformation in mountain belts. In this class of models, the Tibetan Plateau thickens and grows continuously, but no strike-slip faulting is, and can be generated, in marked contrast with observations. Evidence for large décollement between the crust and the lithospheric mantle, which is now advocated on the basis of seismic imaging, also raises doubts on the usefulness of this type of modelling.

Distributions of elevation calculated from the thin sheet model and observed in Asia.

Fig. 1.5. Continuum 3D model showing stress field and deformation of the Asian plate, as well as Tibetan topography. Top: numerical elevations for thin sheet with high stress-strain rate and less convergent amount; middle: elevations in Asia; bottom, numerical elevations for thin sheet with low stress-strain rate and

more convergent amount. The color contour shows the elevations and unit is kilometer. (England and Houseman, 1986; Houseman and England, 1986).

In fact, technically, continuous FEM is definitely not a suitable approach to address the complex geological deformation of collisional Asia, which includes coeval strike-slip faulting, mountain, and plateau building, uplifting, gravitational collapse and normal faulting simultaneously. FEM is popularly used to simulate mostly elastic deformation of homogeneous material. With some modification, for example faults initially placed inside the model, it may be able to investigate fault propagation on a relatively small scale. But, this method is poorly adapted to simulate fault nucleation and propagation on a large scale, which is essential for an accurate description of the Asian plate deformation.

(3) Lower crustal flow models

Royden et al. (1997, 2008) proposed a model, also based on the FEM approach, to simulate long-term (40 Myrs) Asian deformation. The main new assumption is that the lower crust is very weak, and decoupled from both the upper crust and the upper mantle (Clark and Royden, 2000; Cook and Royden, 2008) (Fig. 1.6). This model suggests that the Himalayan range and the Longmen Shan, west of the Sichuan Basin rose due to lower crustal flow: i.e. weak lower crust beneath already thickened regions flow laterally underneath the upper crust of regions where that crust still has normal continental thickness. This type of model was also used to account for mid-crustal deformation in the Himalayan range (Searle and Szulc, 2005; Searle et al., 2011).

Fig. 1.6. 3D deformation model including lower crustal flow proposed to explain both Tibet topography and bulk deformation around India (Cook and Royden, 2008).

Cook and Royden (2008) also use FEM to simulate the different geological issues in Asia (strike-slip faulting, plateau generation and mountain uplift). Without significant changes in the approach, they introduce changes in material behavior with depth in order to include vertically heterogeneous material properties. They input two “fixed” rigid blocks in the model in order to force strike-slip shear along their boundaries. Under such conditions, the generation of new faults is pre-determined at steady, fixed locations. The results are therefore entirely pre-determined by initial conditions.

(4) Stepwise rise and growth of the Tibetan plateau

This model is based on the variable ages of deformation (thrusting, uplift and strike-slip faulting) north of India (Meyer et al., 1998; Tapponnier et al., 2001; Liu-Zeng et al., 2008) (Fig. 1.2). The age data and the fault geometry imply that the Tibetan plateau is composed of three sub-plateaus generated step-by-step from south to north, coevally with the successive activation and northwest propagation of three main strike slip faults (Red River, Kunlun and Altyn Tagh faults). This model comprehensively considers both horizontal and vertical deformations in the Asian plate, and is based on many reliable, consistent field observations (Tapponnier et al., 1982, 1990a; Avouac et al., 1993; Lacassin et al., 1993, 1997, 1998; Leloup et al., 1995; Armijo et al., 1996; Wittlinger et al., 1998, 2004; Leloup et al., 2001; Replumaz et al., 2001).

The computational FEM models seem to mimic the thickening of the Tibetan plateau. Such thickening, however, is smoothly distributed and bounded unless predetermined limits are introduced. Simulating the Tibetan stepwise growth is beyond the reach of FEM models. To reach this target, computational geophysics must explore a more suitable approach, which has the ability to simulate fault nucleation, propagation and motion, together with crustal thickening, in a frame work of large deformation. A promising approach to address large-scale faulting and crustal/lithospheric thickening is the Discrete Element Method (DEM) (Cundall, 1988; Donzé et al., 1994; Morgan and Boettcher, 1999; Finch et al., 2003; Hardy and Finch, 2005; Kozicki and Donzé, 2008, 2009; Plassiard et al., 2009; Scholtès et al., 2011, 2012, 2013; Dean et al., 2013; Gray et al., 2014). This approach is able to simulate continental deformation as governed by the motion of coherent blocks separated by large faults, with the blocks

themselves capable of deforming and the faults to interact. DEM modelling of continental tectonics is able to explore the nucleation and propagation of such faults, and their variable kinematic compatibility, together with simultaneous plateau uplift and with crustal thickening.

1.2 Volcanic Seismicity and degassing during silicic spine extrusions

Before and during silicic spine extrusions (Fig. 1.7a), volcanic earthquakes often occur very frequently, usually in swarms. Such highly periodic, repeatable, and apparently non-destructive sources are often located at fairly constant depth under the crater. The steady position of such volcanic seismicity and the fully degassed nature of the central part of the extruded spine magma cannot be simply accounted for by faulting of only cold host rocks along the conduit margins of the ascending magma (*Lahr et al., 1994; Chouet, 1996; Voight et al., 1998*), and by ring escape of gas around the crater rims coupled with slip along the conduit walls (*Jellinek and Bercovici, 2011*). Brittle-ductile fault textures observed in silicic lavas imply fracturing/faulting within the magma itself (Fig. 1.7b) (*Tuffen and Dingwell, 2005; Green et al., 2006; Neuberg et al., 2006; Tuffen et al., 2008; Thomas and Neuberg, 2012; Vargas-Bracamontes and Neuberg, 2012; Kendrick et al., 2013; Pallister et al., 2013*).

Recent studies at Montserrat and Mt. St Helens suggest that the volcanic seismic events occur in a transitional zone along the conduit wall. Such studies imply that faulting is uniformly distributed along the wall, where hot magma shears past cold host-rock (*Heiken et al., 1988; Jousset et al., 2004; Green et al., 2006; Chouet and Matoza, 2013; Pallister et al., 2013; Kendrick et al., 2014*).

Following this interpretation however, the reason why the seismic events would occur at fixed depths, remains a mystery.

Here, in keeping with a suggestion by Thomas and Neuberg (2012), we test whether volcanic seismic events are caused by a conduit geometry change. We use the Discrete Element Method to simulate silicic magma ascent across a “wide-to-narrow” conduit restriction. The simulation results show that the fracturing or faulting inside the solid magma within the conduit happens where that magma is forced to shrink across the restricted conduit, in agreement with the theoretical and experimental behaviour observed for hot-metal necking and predicted by Slip-Line Field theory (*Johnson et al., 1970; Backhofen, 1973*).

Fig. 1.7. Volcanic spine eruption: a) left, silicic spine extrusion of Mount St. Helens in 2005 (USGS, 2008). B) right, irregular fractures in obsidian caused by shear in ascending magma (Neuberg et al., 2006).

In summary, in this thesis, we describe our work on simulating large-scale faulting and lithospheric thickening in the India-Asia collision zone, and at a smaller scale, the faulting behavior of solid magma during volcanic spine eruptions.

In Chapter 2, we specially describe the methodology, calibrate the code, discuss the parameter effects, and validate the method and the code on a 2D model of continental deformation.

In Chapter 3, we simulate the India-Asia collision zone in 3D. We first summarize the main effects of the collision and the most important, large-scale geological features inside the Asian plate. Next, using the method and parameters validated in Chapter 2, we set up a 3D model, scale the parameters with respect to gravity, and discuss the interface strength between the indenter and model. We then present our modeling results, and compare them with existent observations. Lastly, we summarize the interactions and interdependent frequencies of strike-slip faulting and vertical thickening in the model.

In Chapter 4, we perform and discuss the volcanic spine extrusion simulation. We apply our code to address faulting during volcanic eruptions. We analyze the seismicity data of Mount St. Helens during 2004-2006, and discuss the fault plane solutions of individual seismic events. We propose mechanisms for the sources of several distinct families of earthquakes. We interpret the dominant thrust faulting mechanisms to reflect shrinking in the conduit. We use the Discrete

Element Method to simulate fault growth and propagation during the volcanic eruption.

Finally, in Chapter 5, we summarize our main results from the two simulation studies and reflect on future useful applications of the DEM technique.

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Chapter 2 The discrete element method

(DEM) approach

To simulate the origin and localization of faulting, the mechanical behavior of the lithosphere and crust is approximated by the discrete element method (DEM), a numerical approach initially introduced by Cundall and Strack (Cundall and Strack, 1979; Donzé et al., 1994; Donzé et al., 1996). The material is represented as an assembly of particles (elements) interacting with each other according to pre-defined interaction laws. The overall behavior of the simulated domain is governed by the motion of its constitutive particles which is ruled by Newton's second law.

Thanks to its capability to explicitly describe failure processes, the DEM is now commonly used in civil and geotechnical engineering to study the behavior of geomaterials, either frictional (soils) (Cundall and Strack, 1979; Iwashita and Oda, 1998; Belheine et al., 2009) or brittle (e.g. rock, concrete) (Donzé et al., 1994; Potyondy and Cundall, 2004; Luding, 2008; Scholtès and Donzé, 2012, 2013). DEM modeling has also been applied to study geological processes at a larger scale. For instance, DEM has been used to simulate fold formation and associated cracking (Finch et al., 2003, 2004; Hardy and Finch, 2005, 2006), graben generation (Seyferth and Henk, 2006) and, more generally, shear and thrust faulting by a large amount of authors as a digital analog for sand box experiments (Morgan, 1999; Morgan and Boettcher, 1999; Guo and Morgan, 2004; Morgan, 2004; Cardozo et al., 2005; Morgan and McGovern, 2005a, b; Guo and Morgan, 2006; Morgan, 2006; Guo and Morgan,

2007; Oakley et al., 2007; Guo and Morgan, 2008; Fournier and Morgan, 2012; Dean et al., 2013; Zhang et al., 2013; Gray et al., 2014; Waltz et al., 2014).

The following sections summarize the principal aspects of the DEM and its implementation in the **Yet Another Dynamic Engine** (Yade) Open DEM, the open source code used during this PhD. thesis (Kozicki and Donzé, 2008, 2009; Šmilauer, 2015), and present how the method has been enhanced to tackle the simulation of large tectonic deformation.

2.1 DEM algorithm and calculation

2.1.1 Introduction

The open source software Yade Open DEM provides the calculation platform. The computation parts are written in C++ and the user interface is written in Python to ease scene construction, simulation control, post processing and debugging.

The DEM discretizes the medium under consideration into an assembly of rigid spherical elements, interacting with each other according to the interaction laws defined at their points of contact (Fig. 2.1.1). Many different interparticle laws are available in Yade, each making adjustments related to the phenomenon involved in the physical problems they have been developed for. For instance, Yade has been applied to study the constitutive behavior of granular geomaterials in either dry (Sibille et al., 2008; Belheine et al., 2009; Plassiard et al., 2009) or partially saturated state (Scholtès et al., 2009a; Scholtès et al., 2009b), granular avalanches (Favier et al., 2009a; Favier et al., 2009b), the compaction of metallic powders (Harthong et al., 2009; Jerier et al., 2010), damage and fracturing processes taking place in concrete (Hentz et al., 2004a; Hentz et al., 2004b; Shiu et al., 2009; Nitka and Tejchman, 2015) and rocks (Scholtès

and Donzé, 2012; Duriez et al., 2016) and, more recently, poromechanics of saturated granular materials (Catalano et al., 2014; Scholtès et al., 2015). The interparticle behavior is usually decomposed such that the contact forces have a normal and a tangential component with respect to the contact plane (Fig. 2.1.1), with the additional possibility to consider bending and twisting moments too.

Fig. 2.1.1. Illustration of material discretization process (modified after (Hentz et al., 2004b; Belheine et al., 2009))

2.1.2 The calculation cycle

In a typical DEM simulation, the calculation cycle can be decomposed into four main steps related respectively to, the determination of the position of the constitutive elements, the determination of their potential interaction, the computation of the forces applied to each of them according to the predefined interaction laws and the calculation of their updated position through the integration of the equations of motion (Fig. 2.1.2). Basically, the calculation cycle is repeated iteratively until the simulation stops.

Fig. 2.1.2. Typical simulation loop: each step begins at bodies at 11 o'clock, continues with interaction detection, force application, integration of the equations of motion and ends with position update (modified after (Šmilauer, 2015))

The computational cost is mainly due to the detection of the contacts taking place within the numerical assembly (Fig. 2.1.3a). Once the contacts are detected, forces are then computed according to the predefined contact laws before being applied to the particles. External forces as, for example, gravity or boundary forces can be considered too (Fig. 2.1.3b).

Fig. 2.1.3. (a), left: contacts between spherical elements; (b), right: contacts between spherical elements and the boundaries.

2.1.2.1 Computation cycle

The integration of the equations of motion is done by using an explicit scheme based on a second order finite-difference scheme. Once the resultant force and resultant moment applied on each particle are determined, Newton's second law is applied to compute their translational and rotational accelerations at time t (Catalano et al., 2014). For illustration purpose, we develop here the calculations of translational motion. One has to keep in mind that the rotational motion is computed in a similar way.

First, the acceleration of each particle i , $\ddot{x}_i$ is computed as

$$\ddot{x}_i = F_i/m \quad (2.2.1)$$

with F_i the force applying on the particle and m the mass of the particle. Its velocity is then evaluated at time $t + \Delta t/2$ using a second order finite-difference scheme such that:

$$\dot{x}_i^{[t+\Delta t/2]} = \dot{x}_i^{[t-\Delta t/2]} + (\ddot{x}_i^{[t]} + g) \cdot \Delta t \quad (2.2.2)$$

where $\dot{x}_i^{[t+\Delta t/2]}$ and $\dot{x}_i^{[t-\Delta t/2]}$ are the velocities at time $t + \Delta t/2$, and $t - \Delta t/2$ respectively, $\ddot{x}_i^{[t]}$ is the acceleration at time t , g is the gravitational acceleration and Δt is the time step. Finally, Equation (2.2.2) is integrated over time and the final position x_i of each particle is updated as:

$$x_i^{[t+\Delta t]} = x_i^{[t]} + \dot{x}_i^{[t+\Delta t/2]} \cdot \Delta t \quad (2.2.3)$$

with $x_i^{[t+\Delta t]}$ and $x_i^{[t]}$ the position of particle i at time $t + \Delta t$ and t respectively.

2.1.2.2 Damping

Because of the dynamic formulation of the method (explicit time domain integration), a global non-viscous damping is used to dissipate kinetic energy and

facilitate convergence towards quasi-static equilibrium. This damping directly acts on the forces (torques respectively) considered in the equations of motion so that the displacements are calculated from the damped force whose components are computed such that

$$F_i^d = \mathbf{F}_i - D_a \cdot |F_i| \cdot \text{sign}(\dot{x}_i)$$

$$\begin{cases} \text{sign}(a) = -1, & a < 0 \\ \text{sign}(a) = 1, & a > 0 \\ \text{sign}(a) = 0, & a = 0 \end{cases} \quad (2.2.4)$$

with D_a a dimensionless parameter ranging from 0 to 1, $D_a=0$ corresponding to a totally undamped system and $D_a=1$ to a static one. D_a had been previously presented as a parameter that would describe physical energy dissipation and that could thus be calibrated according to, e.g., the seismic quality factor of the material under consideration (Potyondy and Cundall, 2004). No clear evidence was given however concerning the relationship between the physical and the numerical quantities. Damping is thus considered here, as in most other studies, only as a convenient numerical tool to ensure the quasi-staticity of the simulations.

2.1.2.3 Critical time step

In addition, the time step must be chosen so that the numerical stability of the explicit numerical scheme is ensured. The critical time step above which the stability of the numerical scheme is not ensured can be generally defined (Šmilauer, 2015) as

$$\Delta t_{cr} = 2/\omega_{max} \quad (2.2.5)$$

with ω_{max} the highest eigenfrequency within the system.

Considering a particle packing as a general mass-spring system where particles have a mass m_i and are connected through springs with a stiffness K_i , the overall critical timestep can be computed as

$$\Delta t_{cr} = \min_i(\sqrt{2} \cdot \sqrt{m_i/K_i}) \quad (2.2.6)$$

Here, K_i is the stiffness of the contact between particles. In our simulations, we therefore ensured that the time step was always below this critical value.

2.1.3 The interparticle behavior

The behavior of every DEM model is controlled by the behavior defined at the interparticle scale. The contact laws (or interaction laws) governing the interparticle behavior relate the forces to the displacements of the particles and thus the deformation and failure of the simulated medium. Contact laws are thus an essential part of DEM simulations and are sometimes referred to as “constitutive laws” even though they are just a component of what defines the constitutive behavior of the simulated material, the microstructure of the numerical medium (or particle arrangement) being another one (see section 1.3). At the contact point, normal, tangential, and rolling contact models can be taken into consideration (Fig. 2.1.4). For the present study, we did not consider the rolling contact model to keep the model as simple as possible and to limit the number of parameters.

Fig. 2.1.4. Contact model in the DEM with Moment Transfer Law (Belheine et al., 2009)

As in most DEM models, the interparticle behavior of our DEM model can be decomposed into the normal and tangential directions of the contact plane (Fig. 2.1.5). The normal contact model considers both divergence and convergence cases (Fig. 2.1.6). In the convergence regime (compression of the contact/bond), the normal force is computed as

$$F^n = K_n \cdot U_n \quad (2.3.1)$$

with U_n the normal component of the relative displacement between particles A and B, and K_n the normal stiffness derived from the properties assigned to the particles such that:

$$K_n = \frac{2 \cdot E_A \cdot R_A \cdot E_B \cdot R_B}{E_A \cdot R_A + E_B \cdot R_B} \quad (2.3.2)$$

where R_A and R_B are the radii of the particles and E_A and E_B their respective elastic modulus E which directly relate to the bulk modulus of the simulated medium.

In the divergence regime (extension of the contact/bond), the normal force calculation in the elastic stage is produced using the same stiffness as the one defined in the convergence regime. The interparticle distance can increase up to $U_n^{tensile}$ for which the maximum admissible tensile force F_{max}^n is reached:

$$F_{max}^n = t \cdot A_{int} \quad (2.3.3)$$

with t the tensile strength of the interparticle bond and $A_{int} = \pi \cdot (\min(R_A, R_B))^2$ the interacting surface area between A and B. When F_{max}^n is reached, the force is not set to zero immediately as it is usually the case when modeling brittle rocks (see for instance [Scholtès and Donzé, 2013]). Instead, F^n gradually decreases to describe a softening behavior at the particle scale that takes place when $U_n^{tensile} < U_n < U_n^{rupture}$ according to:

$$F^n = F_{max}^n - \frac{K_n}{s}(U_n - U_n^{tensile}) \quad (2.3.4)$$

with s a weakening coefficient that needs to be defined. If the interparticle distance continues to increase, the interparticle bond breaks when $U_n > U_n^{rupture}$ and all forces are set to zero including the tangential force (see afterward). A crack is then defined at the location of the bond breakage. As illustrated later on, the weakening coefficient s controls the dilatation of the material. With greater s values, the deviation between particles is restricted, resulting in a decrease of the material brittleness and subsequent reduction of its dilation. This feature constitutes an essential component of our DEM model since it enables to control the failure mode of the simulated medium (e.g. the plastic behavior of the tectonic plate in Chapter 3, the brittle behavior of the solid magma in Chapter 4).

Similarly to classical DEM formulations (Hart et al., 1988), the tangential force at the current time step is computed incrementally such as

$$F^s(t) = F^s(t-\Delta t) + K_s \cdot \Delta U_s \quad (2.3.5)$$

with $F^s(t-\Delta t)$ the force computed at the previous time step. ΔU_s is the incremental tangential displacement between A and B and defined as $\Delta U_s = U_s^t - U_s^{t-\Delta t}$ and K_s is the tangential stiffness defined as $K_s = a \cdot K_n$ with a , a coefficient which directly affects the Poisson's ratio of the simulated medium (Plassiard et al., 2009).

As for the normal behavior, a maximum admissible tangential force F_{max}^s is defined equal to:

$$F_{max}^s = c \cdot A_{int} \quad (2.3.6)$$

with c the interparticle cohesion. One can note that Equation (2.3.6) corresponds to Mohr Coulomb criterion for the particular case where the friction angle is equal to 0 (or to the failure envelope commonly approved to describe the undrained behavior of clay). In our model, two scenarios can be considered when the tangential force reaches the maximum tangential force:

- The tangential force stays equal to its maximum value until the maximum admissible normal force is reached (configuration used for the modeling of the tectonic plates' plastic behavior).
- The interparticle bond breaks and the forces are set to zero (configuration used for the modeling of the magma's brittle behavior)

In addition, a parameter is introduced that controls the possibility for newly created interparticle contacts to heal. For instance, new contacts occur during the deformation process as a result of particles movement enabled by the breakage of the

initial interparticle bonds. When new contacts are detected, a fresh bond will be created if the two spheres overlap. This bond has the same strength as the previous one. This process can be thought of a way to reproduce the healing processes taking place along an active fault. The fault could have a plastic behavior due to changes in pressure, temperature and time. Healing processes along the fault might include cooling, recrystallization, fluid extraction, and hardening. One can mention at this point that for large s values, which is a weakening coefficient (see more details in Fig. 2.1.6b), a particle would be able to bond with its neighbors while being still bonded to its previous neighbor. This is a way to avoid the dilatancy of fault zones when sheared (see the s value test in section 2.3.2).

Fig. 2.1.5. The normal and shear contact models

(a)

(b)

(c)

(d)

Fig. 2.1.6. Mechanical response of the contact model: (a) normal behavior for convergence; (b) normal behavior for divergence; (c) tangential behavior for brittle materials; (d) tangential behavior for plastic materials.

2.1.4 Building a DEM model

Once the interaction laws are defined, the domain of interest needs to be discretized. In our case, two configurations need to be defined: one where the tectonic plates are the domain of interest and another one where the magma is the domain of interest. We thus have to build up assemblies of spherical particles representative of these two configurations. To build up such models, the domain is defined as a closed box where a cloud of particles is initially generated. The particles are placed randomly inside the prescribed volume such that they do not overlap one with each other. The number of particles and their size distribution are defined at this stage. In our case, we used a homogenous particle size distribution such as the ratio between the maximum and the minimum particle radii is equal to 2. The number of particles can be adjusted with respect to the desired level of discretization keeping in mind that the computational cost is directly related to the number of particles, more particles leading to higher computational cost (in both terms of memory and time). An internal expanding (particle growing) technique is then used in order to densify the medium. Each particle radius is increased progressively up to the point where a targeted stress is applied by the particles on the boundaries. During this dynamic process, the particles interact through frictional contacts only (no cohesion); the smaller the coefficient of friction is (see section 2.3, 2.4 and 3.2), the denser the final packing will be. A convergence criterion needs to be defined to check whether the final packing is ready. In addition to the required targeted stress, we check the unbalanced force of the whole system. The unbalanced force is a key value that enables to check if the system is in a static or in a dynamic state. The unbalanced force is the ratio of mean resultant force on bodies to that resulting from the interactions. For perfectly static equilibrium, the resultant force on all bodies should be zero. The unbalanced force will thus tend to zero

if the simulation stabilizes. Nonetheless, zero is never reached because of finite precision computation. Sufficiently small values of the unbalanced force (e.g. 0.01 N or smaller) can thus be considered as representative of a quasi-static state. When the unbalanced force is less than a given value, the packing is thus stable (Fig. 2.1.7). Before being submitted to further loading, the packing is set to be stress free by resetting all the forces applied on each particle. The physical properties are then assigned to the particles and the contacts can be detected to set up the initial network of interparticle bonds. Thanks to a special feature available in Yade dedicated to enable for near neighbor interaction, the bonds are built between pairs of particles for which the interparticle distance is less than a predefined distance defined as

$$\gamma_{int} \cdot (R_A + R_B)$$

where γ_{int} is the interaction range coefficient which can be adjusted depending on the targeted behavior. In order to avoid spheres embedded in between interacting pairs, the interaction range should not be greater than the one defined by the relative distribution of sphere diameters inside the medium. Scholtès and Donzé's (2013) suggest that γ_{int} must be less than 1.5, if $R_{max}/R_{min}=2$, and we use this parameterization in our models. For a given packing, the interaction range coefficient also decides the number of bonds per particle, which is also referred to as the coordination number N (Fig. 2.1.8). The coordination number has been proven to influence the brittleness of the simulated behavior [Scholtès and Donzé, 2013]. Given the contribution of brittle fracturing in tectonic deformation, γ_{int} is thus a parameter that could affect the fault propagation in our models. Its contribution will be discussed afterward, in a later section (section 2.3.1). The coordination number is one of the key factors to ensure different models to produce similar behaviors. For that matter, we need to ensure that the coordination number is equal for all packings but also that the size distribution and the porosity of the packings are the same.

Once the interparticle bonds are created, the distance between the centers of the interacting particles is defined as the equilibrium distance U_{eq} . When the medium is subjected to deformation (through external loading for example), the relative displacement U_n between the particles is computed as

$$U_n = U_0 - U_{eq} \quad (2.4.1)$$

where U_0 corresponds to the initial distance between the centers of the particles. U_n is used for calculating the interparticle forces (see section 2.1.3).

Fig. 2.1.7. Discretization of the simulated medium as an assembly of particles and illustration of an interparticle interaction: a/Top left, the India-Asia collision zone (Peltzer and Tapponnier, 1988); b/Top right, the interpretation of the discretized

assembly (Hentz et al., 2004b); c/Bottom right, zoom in of the contacting spheres;
d/Bottom left, contact forces and geometry.

Fig 2.1.8. Illustration of the relationship between the interaction range coefficient and the coordination number: (a) $\gamma_{int} = 1$ and (b) $\gamma_{int} > 1$, and (c) 3D view of the bond network (modified after (Scholtès and Donzé, 2013)).

2.2 Testing the interparticle law

This section is dedicated to the testing of the interparticle law described in the previous section. We illustrate here the implementation of the interaction range coefficient and investigate the interparticle behavior in both the normal and tangential directions. We also illustrate how the healing function works at the particle scale.

For the following tests, the damping value D_a was set to 0.4 (see section 2.1.2.2), and the time step chosen equal to $0.4 * \Delta t_{cr}$ to ensure the stability of the system (see section 2.1.2.3).

2.2.1 Interaction range coefficient

We use the interaction range coefficient γ_{int} to determine the coordination number in the model. Using the interaction range coefficient, we can generate bonds

between particles that are either: tangentially contacting (Fig. 2.2.1a), overlapping (Fig. 2.2.1b) or even non-contacting (Fig. 2.2.1c), if the gap between the particles is smaller than $(\gamma_{int} - 1) \cdot (R_p + R_y)$.

Fig. 2.2.1 Illustration of bond configuration between 2 particles: a/Left, tangentially contacting; b/Middle, overlapping; c/Right, non-contacting.

2.2.2 Normal behavior

The normal behavior can be divided in two distinct phases corresponding respectively to diverging and converging displacement between the interacting particles. The set of parameters used for this study is given in Table 2.2.1.

Table 2.2.1 Parameters for normal behavior test

Parameter	Symbol	Value	Unit
Radii of elements	R_i	1	[m]
Particles' elastic modulus	E	300,000	[Pa]
Interaction range coefficient	γ_{int}	1.22	[-]
Tensile strength	t	300	[Pa]
Weakening coefficient	s	10	[-]

Divergence

We set two particles (purple and yellow spheres) with an initial gap along the y direction ($x_p = x_y$ and $y_p = y_y + 2 \cdot R_p$) (Fig. 2.2.2a). The two particles are initially in contact together (tangential contact here but the same behavior would apply for the conditions given in section 2.2.1), and a bond is thus generated between them. In Yade, the tension force is defined as negative, and the compression force is positive. The magnitude of the normal force between them varies from 0 to the maximum value defined according to the parameter t and then drops to 0 according to the softening coefficient defined in section 2.1.3 (Fig. 2.2.3).

Fig. 2.2.2 Illustration of the normal interparticle behavior taking place between a pair of particles when they are diverging (the contact law is defined in section 2.1.3).

Fig. 2.2.3 Top, Relationship between the normal force and the normal displacement when bonded particles are diverging (see Fig.2.2.2), Bottom, Relationship between the normal force and the calculation steps.

Convergence

For the case where the particles converge toward each other, the normal force increases proportionally to the normal displacement between the two elements without any limitation as illustrated in Fig. 2.2.4 and Fig. 2.2.5.

Fig. 2.2.4 Illustration of the normal interparticle behavior taking place between a pair of particles when they are converging (the contact law is defined in section 2.1.3)

Fig. 2.2.5 Top, Relationship between the normal force and the normal displacement

when bonded particles are converging (see Fig.2.2.4), Bottom, Relationship between the normal force and the calculation steps.

2.2.3 Tangential (shear) behavior

To illustrate how the particles behave when submitted to shear, we consider two configurations

- The case where the particles are initially not in contact
- The case where the particles are initially in contact (either tangentially contacting or overlapping)

For each configuration, we consider two different cases for which the ratio between the interparticle cohesion c and the tensile strength t is either high or low. The set of parameters used for this study is given in Table 2.2.2.

Table 2.2.2 Parameters for testing the shear behavior of the interparticle law

Parameter	Symbol	Value	Unit
Radii of elements	R_i	1	[m]
Interaction range coefficient	γ_{int}	1.22	[-]
Particles' elastic modulus	E	300,000	[Pa]
Tangential stiffness coefficient	a	0.004	[-]
Tensile strength	t	300	[Pa]
Cohesion	c	50/1000	[Pa]
Weakening coefficient	s	10	[-]

Particles initially not in contact with a high c/t ratio

We set two spherical elements (purple and yellow spheres) with an initial gap along the y direction ($x_p = x_y$ and $y_p = y_y + 2 \cdot R_i + \Delta$ with $\Delta = 0.02 \cdot R_i$) and a third particle (blue) aside the yellow one ($x_b = x_y + 2 \cdot R_i$ and $y_b = y_p$) (Fig. 2.2.6a). The normal distance between the two centers of spherical elements is less than the sum

of the two radii times the interaction range coefficient ($y_p - y_y < \gamma_{int} \cdot (R_p + R_y)$) in order to generate a bond between the purple and yellow spheres at the first iteration (Fig. 2.2.6a). One has to note that the interaction range coefficient is only used at the first iteration of the simulation so that new contacts can be created only between contacting or overlapping particles. We apply a constant velocity ($v_p = 100$ [m/s]) on the purple element so that it moves horizontally. At the beginning of the displacement, both the normal force and the shear force increase proportionally to the displacement (Fig. 2.2.7 and Fig. 2.2.6b, c). Since the c/t ratio is high, the normal force reaches its maximum value before the shear force and it weakens/softens down to zero according to the weakening coefficient s (Fig. 2.2.6). Then, when the normal interparticle distance is greater than the normal rupture distance (see section 2.1.3), the interparticle bond breaks and the forces are both set to zero (Fig. 2.2.6d). The purple element then continues to move and passes nearby the blue element (Fig. 2.2.6e). Because the interaction range coefficient is not active anymore, only strictly contacting particles can interact. The purple element thus continues its way and passes over the blue one without interacting with it.

(d) step 4

(e) step 20

Fig. 2.2.6. Illustration of kinematics and interparticle bond behavior for particles initially not in contact and with a high c/t ratio. The velocity of the purple particle is 0.01 m/s towards the right side.

Fig. 2.2.7. Forces acting between the purple and yellow spherical elements for the case where they are not initially in contact and with a high c/t ratio: a/Top: normal force versus normal displacement; b/Middle: shear force versus shear displacement; c/Bottom: normal and shear forces versus the calculation steps.

Particles initially not in contact with a low c/t ratio

Like for the previous case, an interparticle bond is built between the purple and yellow spheres at the first iteration (Fig. 2.2.8a). The normal and shear forces then increase proportionally to the displacement as the purple particle moves (Fig. 2.2.8b and Fig. 2.2.9). After the normal force reaches its maximum admissible value, it weakens according to the softening coefficient (Fig. 2.2.8c and Fig. 2.2.9). Nonetheless, because the cohesion of the bond is low with respect to its tensile strength, the shear force reaches its maximum value before the normal force vanishes and plateaus (Fig. 2.2.9). The bond finally breaks when the normal rupture distance $U_n^{rupture}$ is reached (Fig. 2.2.8d). As for the previous case, the purple and the blue particles do not interact because they never come into contact one with another. The purple particle thus passes over the blue one (Fig. 2.2.8e).

The difference with the previous case lies in the fact that we defined here a low c/t ratio. The shear force then reaches its maximum value and plateaus before the bond breaks (Fig. 2.2.9). The bond breaks here due to the limitation of the bond strength in the normal direction of the contact.

Fig. 2.2.8. Illustration of kinematics and interparticle bond behavior for particles initially not in contact and with a low c/t ratio. The velocity of the purple particle is 0.01 m/s towards the right side.

Fig. 2.2.9. Forces acting between the purple and yellow spherical elements for the case where they are not initially in contact and with a low c/t ratio: a/Top: normal force versus normal displacement; b/Middle: shear force versus shear displacement; c/Bottom: normal and shear forces versus iterations.

Particles initially in contact with a high c/t ratio

The purple and yellow particles are positioned such that they are in contact one with each other ($x_p = x_y$ and $y_p = y_y + 2 \cdot R_i$). The blue particle is placed at the same position aside the yellow one ($x_b = x_y + 2 \cdot R_i$ and $y_b = y_p$) (Fig. 2.2.6a). A bond is generated between the purple and yellow spheres at the first iteration since the condition ($y_p - y_y < \gamma_{int} \cdot (R_p + R_y)$) for its creation is respected (Fig. 2.2.10a). Again, as the purple particle moves horizontally toward the right side, the normal and shear forces both increase proportionally to the displacement (Fig. 2.2.11 and Fig. 2.2.10b, c). Like for case 1, because the cohesion is high, the shear force does not reach its maximum admissible value before the normal maximum force is reached. The normal force thus weakens to zero (Fig. 2.2.11) and the bond finally breaks once the normal rupture distance is reached (Fig. 2.2.10d). The purple particle then continues its way and comes into contact with the blue one (Fig. 2.2.10e). Because of the healing possibility, a new bond is then created between the purple and the blue particles. The forces acting between these two particles follow then the same behavior as the ones acting between the purple and the yellow one previously (the three subplots at the left side of Fig. 2.2.11). Once the normal rupture distance is reached, this newly created bond then breaks and the forces are set to zero (Fig. 2.2.10g and h). The healing function thus works only for the case where particles come in strict contact. Healing is active during all the simulation thus allowing for the creation of new bonds every time two particles come in contact one with another. This local process is introduced so as to limit the dilatancy along a plane of shearing and is aiming at representing the actual healing observed along active faults due to physico-chemical processes.

Fig. 2.2.10. Illustration of kinematics and interparticle bond behavior for particles initially in contact and with a high c/t ratio. The velocity of the purple particle is 0.01 m/s towards the right side.

Fig. 2.2.11. Forces acting between the purple and yellow spherical elements and between the purple and blue spherical elements for the case where they are initially in contact and with a high c/t ratio: a/Top-left: normal force versus normal displacement between the purple and yellow elements; b/Top-right: normal force versus normal displacement between the purple and blue elements; c/Middle-left: shear force versus shear displacement between the purple and yellow elements; d/Middle-right: shear force versus shear displacement between the purple and blue elements; e/Bottom: normal and shear forces between the purple and yellow elements (forces for initial bond) as well as normal and shear forces between the purple and blue elements (forces for healed bond) versus iterations.

Particles initially in contact with a low c/t ratio

Like for the previous case, the purple and yellow spheres are initially in contact and healing is activated once the purple and the blue particles come in strict contact one with each other. The difference lies here in the fact that the interparticle bond breaks after the shear force plateaus (Fig. 2.2.12 and 2.2.13). The same behavior can be observed for the newly created (healed) bond between the purple and blue particles (the three subplots at the left side of Fig. 2.2.13).

Fig. 2.2.12. Illustration of kinematics and interparticle bond behavior for particles initially in contact and with a low c/t ratio. The velocity of the purple particle is 0.01 m/s towards the right side.

Fig. 2.2.13. . Forces acting between the purple and yellow spherical elements and between the purple and blue spherical elements for the case where they are initially in contact and with a low c/t ratio: a/Top-left: normal force versus normal displacement between the purple and yellow elements; b/Top-right: normal force versus normal displacement between the purple and blue elements; c/Middle-left: shear force versus shear displacement between the purple and yellow elements; d/Middle-right: shear force versus shear displacement between the purple and blue elements; e/Bottom: normal and shear forces between the purple and yellow elements (forces for initial bond) as well as normal and shear forces between the purple and blue elements (forces for healed bond) versus iterations.

2.3. Calibration

The plane-strain indentation model shown in Fig. 2.3.1 is used to understand the influence of the numerical parameters on the fault pattern and overall behavior of the simulated medium. The model setting is similar to the plasticine analogue model used by Peltzer and Tapponnier (Peltzer and Tapponnier, 1988) to simulate the large strike-slip faulting occurring in the Asian plate caused by the collision with India. The model is 22.5 m wide, 30 m long, and 2 m thick. The assembly used is made up of 100 000 particles that follow a uniform size distribution such as the mean radius is 0.123 m and the ratio between the maximum and the minimum radii is equal to 1.86 (about 2). The packing was generated following the growing technique presented in section 2.1.4. The assembly is confined in between two fixed frictionless rigid plates, placed in the front and at the back of the assembly, in order to avoid the thickening of the model and thus ensure plane strain conditions. Two additional fixed frictionless rigid walls are used to block the displacements on the left and at the top of the model. The right side of the model is not restrained by anything and the bottom side is also free. The indentation is produced by a parallelepipedic box whose surface friction can be controlled independently. The width of the indenter is 5 m, and it is located 5 m far from the right corner and 12.5 m far from the left corner of the model. At the beginning of the simulation, the indenter is assigned a predefined velocity along the main direction of the model (from bottom to top) so that it can penetrate the packing.

Fig. 2.3.1. The plane-strain indentation model used to simulate the plasticine experiments from (Peltzer and Tapponnier, 1988)

In order to gain further insights into the effect of the numerical parameters on the material behaviour, we also simulated uniaxial compression tests on a cube whose physical and mechanical properties are similar to the ones of the indentation model (Fig. 2.3.2). Similar to the model in Peltzer et al. (1984) (Peltzer et al., 1984), the cube is $5\text{ m} \times 5\text{ m} \times 2\text{ m}$ and is also confined in between two fixed frictionless rigid walls at the front and at the back to ensure plane-strain conditions. The bottom and top plates are frictionless and move toward each other at a given predefined velocity to compress the assembly. This complementary uniaxial testing has been designed in order to

investigate the mechanical behavior of the numerical/synthetic material through the analysis of the stress-strain curves.

Fig. 2.3.2. The uniaxial compression test model used to gain insights into the mechanical behavior of the simulated/synthetic material; all the stress-strain curves presented in this section result from this model.

Every parameter of the model has been thoroughly tested so as to identify the most relevant set of parameters for simulating the horizontal deformation of the India-Asia collision as described by Peltzer and Tapponnier (Peltzer and Tapponnier, 1988).

The parameter calibration involves the determination of the interaction range coefficient γ_{int} , weakening coefficient s value, elastic modulus E , tensile strength t , cohesion c , tangential stiffness coefficient value a and shortening rate v .

2.3.1 Interaction range coefficient (γ_{int})

In this section, we studied how the interaction range coefficient γ_{int} could influence the predictions of the model. The set of parameters used for this study is given in Table 2.3.1.

Table 2.3.1 Parameters for testing the interaction range coefficient (γ_{int})

Parameter	Symbol	Value	Unit
Number of elements	-	100,000	-
Mean element radius	R	0.123	[m]
Ratio of largest to smallest element	-	1.86	[-]
Interaction range coefficient	γ_{int}	1, 1.05, 1.1, 1.15, 1.2, and 1.22	[-]
Particles' elastic modulus	E	0.3	[MPa]
Tangential stiffness coefficient	a	0.004	[-]
Tensile strength	t	10	[kPa]
Cohesion	c	5	[kPa]
Weakening coefficient	s	10	[-]
Shortening rate of indenter	v	0.01	[m/s]
Damping coefficient	D_a	0.4	[-]
Time interval coefficient	-	0.4	[-]

Total healing has been used in every simulation unless otherwise specified (see sections 2.1.3 and 2.2.3 for details). Total healing means that new interparticle bonds are created when two particles come into contact during the deformation process. These newly created bonds have a strength equivalent to the initial one.

As shown in Fig. 2.3.3, the mechanical response of the model is greatly affected by the value assigned to γ_{int} . When γ_{int} increases, the peak stress increases while the residual stress keeps constant. The softening behavior tends to be more obvious when γ_{int} increases. The slope of the stress-strain curve in the elastic stage

(related to the bulk modulus of the medium) also increases with γ_{int} and the yield strain decreases as γ_{int} increases. γ_{int} thus controls the brittleness of the simulated/synthetic material. As γ_{int} increases, the plastic behavior evolves from strain hardening to perfectly plastic and then to strain softening.

The effect of γ_{int} on the brittleness of the synthetic material can also be identified on the fault patterns obtained with the indentation model (Fig. 2.3.4). As γ_{int} increases, the deformation varies from diffusion (Fig. 2.3.4A, B) to faulting (Fig. 2.3.4C, D) and then to fissuring (Fig. 2.3.4E, F).

When $\gamma_{int}=1$ (Fig. 2.3.4A), the deformation is diffuse throughout the model. When $\gamma_{int}=1.05$, some small faults occur (Fig. 2.3.4B). The deformation in both cases tends to be ductile with no apparent faults or very small faults. None of these faults are able to propagate toward the edge of the model. None of the models show clear evidence of faulting since the material is too ductile.

When $\gamma_{int}=1.1$, faulting is apparently longer and much more obvious (Fig. 2.3.4C). Even though the induced fault does not propagate toward the right edge of the model for the indentation amount illustrated here, the fault nevertheless tends to reach the edge after further displacement of the indenter. Comparing this model (Fig. 2.3.4C) to the previous ones (Fig. 2.3.4A and B), we observe that the conspicuous difference is the fault propagation. With regards to these results, we can conclude that strain hardening is a material characteristic that tends to inhibit faulting.

When $\gamma_{int}=1.15$ (Fig. 2.3.4D), the fault is apparently longer and can propagate toward the edge of the medium to extrude a sub-block. After the block is extruded, it

translates eastward without any rotation. One can note that, according to the stress-strain curves obtained for the two models (Fig. 2.3.3), the plastic behavior changes from perfectly plastic for $\gamma_{int}=1.1$ to little strain softening for $\gamma_{int}=1.15$.

When γ_{int} is fixed to an even bigger value like 1.2 (Fig. 2.3.4E) and 1.22 (Fig. 2.3.4F), more brittle faulting can be observed. For these two cases, the fault does not propagate toward the edge of the assembly. Instead, a longitudinal open crack is generated inside the medium along the direction of the maximum compressive stress. Accordingly, the behavior obtained through uniaxial testing (Fig. 2.3.3) varies from small strain softening for $\gamma_{int}=1.15$ to large strain softening for $\gamma_{int}>1.2$ as indicated by the stress drops occurring after yielding. These stress drops are representative of the brittleness of the material that causes the opening of the models in similar ways to spalling failure observed in brittle rocks.

To sum up, the greater γ_{int} is, the more brittle the material is. γ_{int} is thus directly related to the brittleness of the material.

Fig. 2.3.3. Stress-strain curves obtained from uniaxial compression tests performed with different values of γ_{int} . The residual stresses of this figure as well as the following figures should be constant but they are slowly increasing, which is caused by the increasing loading areas. To calculate the stress, we use the force applying on the loading plate divided by the initial area which is in contact with the loading plate. Here, deformation of the sample is greater than the usual plasticine/analogue experiments (Peltzer and Tapponnier, 1988). The strain goes beyond 0.3 and reaches 0.4. Consequently, the contact area between the sample and the loading plate increases. But we do not take into account this surface change in our calculations. This result in an increase of the residual stress is shown in the above figure.

Fig. 2.3.4. Deformation patterns obtained from plane-strain indentation tests performed for different values of γ_{int} : from diffusion to faulting and then to fissuring as γ_{int} increases.

One can note that for different parameter settings, the effect of γ_{int} may not be exactly the same. Even though the parameter settings are different, the effect of γ_{int} is

similar. Its value thus has to be chosen accordingly to the brittleness of the material under consideration.

2.3.2 Weakening coefficient (s)

In this section, we study the influence of the weakening coefficient s on the model behavior. The set of parameters used for this study is given in Table 2.3.2.

Table 2.3.2 Parameters for testing the weakening coefficient (s)

Parameter	Symbol	Value	Unit
Number of elements	-	100,000	-
Mean element radius	R	0.123	[m]
Ratio of largest to smallest element	-	1.86	[-]
Interaction range coefficient	γ_{int}	1	[-]
Particles' elastic modulus	E	1	[MPa]
Tangential stiffness coefficient	a	0.01	[-]
Tensile strength	t	1	[kPa]
Cohesion	c	1	[kPa]
Weakening coefficient	s	0, 5, 10, 12, 15, and 20	[-]
Shortening rate of indenter	v	0.01	[m/s]
Damping coefficient	D_a	0.4	[-]
Time interval coefficient	-	0.4	[-]

The mechanical response of the simulated/synthetic material is only slightly affected by s with this set of parameters as suggested by the stress-strain curves presented on Fig. 2.3.5. The fault patterns obtained for the plane-strain indentation test are also very similar whatever the s value (Fig. 2.3.6).

Fig. 2.3.5. Stress-strain curves obtained from uniaxial compression tests performed with different values of s .

Fig. 2.3.6. Deformation patterns obtained from plane-strain indentation tests

performed for different values of s .

2.3.3 Elastic modulus (E)

We illustrate here the influence of the elastic modulus E on the model's behavior. The set of parameters used for this study is given in Table 2.3.3.

Table 2.3.3 Parameters for testing the elastic modulus (E)

Parameter	Symbol	Value	Unit
Number of elements	-	100,000	-
Mean element radius	R	0.123	[m]
Ratio of largest to smallest element	-	1.86	[-]
Interaction range coefficient	γ_{int}	1	[-]
Particles' elastic modulus	E	0.3, 1, 5, and 10	[MPa]
Tangential stiffness coefficient	a	0.01	[-]
Tensile strength	t	1	[kPa]
Cohesion	c	1	[kPa]
Weakening coefficient	s	10	[-]
Shortening rate of indenter	v	0.01	[m/s]
Damping coefficient	D_a	0.4	[-]
Time interval coefficient	-	0.4	[-]

The stress-strain curves presented on Fig. 2.3.7 indicate that E does not only affect the slope of the curve in the elastic stage but also affects the peak stress value. This result is expected given the correlation between E and the bulk modulus of the simulated material (Kozicki and Donzé, 2009; Plassiard et al., 2009). As E increases,

the slope of the stress-strain curve becomes steeper as the material is stiffer. Also, the peak stress tends to increase whereas the yield strain tends to decrease due to the fact that the material is stiffer. On the other hand, the residual stress seems to be unaffected. The smaller yield strain means that the model deformation transfers earlier from elastic to plastic. This characteristic can be visualized through the fault patterns obtained in the plane-strain indentation tests.

Indeed, the fault patterns of the models in the first stage of the indentation (in the second column of Fig. 2.3.8) show the first strike-slip fault nucleation and how much indentation amount is needed to generate the fault. This first strike-slip fault (Fig. 2.3.8 A1, B1, C1, and D1) occurs for a displacement of the indenter equal respectively to 5.12 m, to 2.81 m, 1.26 m, and 0.89 m when E increases from 0.3 MPa to 10 MPa. One can observe also that, the angle between the first strike-slip fault and the front of the indenter increases as E increases.

When $E=0.3$ MPa (Fig. 2.3.8A), the first strike-slip fault forms for a displacement of 5.12 m (after 14×10^4 iterations). This strike-slip fault does not open a zone along the fault. For a displacement of 8.43 m (Fig. 2.3.8A2), there is still no open zone along the strike-slip fault. Thus, the offset along the strike-slip fault is too small to open a zone at the end of the strike-slip fault.

When $E=1$ MPa (Fig. 2.3.8B), the first strike-slip fault nucleates for a displacement of 2.81 m and propagates up to the edge of the medium, forming an open zone at the far end of the fault. This opening propagates toward the left edge of the model with further displacement as shown in Fig. 2.3.8B2. The consequence is that it

isolates a sub-block which tends to rotate clockwise when extruded from the main block. It is the rotation of this block that opens the zone along the fault.

When $E=5$ MPa (Fig. 2.3.8C), the first strike-slip fault occurs for a displacement of 1.26 m. For a displacement of 9.18 m, the strike-slip fault propagates toward the right edge and isolates a sub-block which also rotates clockwise. This rotation opens a zone that tends to reduce with further indentation. One can note the presence of small blocks that keeps the sub-block bonded to the main block at the end of the first strike-slip fault.

When $E=10$ MPa (Fig. 2.3.8D), the first fault is generated for a displacement of the indenter of 0.89 m. Similarly to the previous case ($E=5$ MPa), small blocks bond the sub-block to the main block at the end of the fault.

To sum up, one can say that E influences the indentation amount required to form the first strike-slip fault as well as the opening of this strike-slip fault.

Fig. 2.3.7. Stress-strain curves obtained from uniaxial compression tests performed with different values of E .

	Step $14 \cdot 10^4$; the first strike-slip fault	Further deformation
A, $E = 0.3 \text{ MPa}$	1. indentation amount 5.12 m	2. indentation amount 8.43 m (step $23 \cdot 10^4$)
B, $E = 1 \text{ MPa}$	1. indentation amount 2.81 m	2. indentation amount 8.44 m (step $42 \cdot 10^4$)
C,	1. indentation amount 1.26 m	2. indentation amount 9.18 m (step $102 \cdot 10^4$)

Fig. 2.3.8. Deformation patterns obtained from plane-strain indentation tests

performed for different values of E .

2.3.4 Tensile strength (t)

We study here the influence of the interparticle tensile strength t on the model's predictions. The set of parameters used for this study is given in Table 2.3.4.

Table 2.3.4 Parameters for testing the tensile strength (t)

Parameter	Symbol	Value	Unit
Number of elements	-	100,000	-
Mean element radius	R	0.123	[m]
Ratio of largest to smallest element	-	1.86	[-]
Interaction range coefficient	γ_{int}	1	[-]
Particles' elastic modulus	E	1	[MPa]
Tangential stiffness coefficient	a	0.01	[-]
Tensile strength	t	0.3, 0.5, 1, 1.2, 1.5 and 10	[kPa]
Cohesion	c	1	[kPa]
Weakening coefficient	s	10	[-]

Shortening rate of indenter	v	0.01	[m/s]
Damping coefficient	D_a	0.4	[-]
Time interval coefficient	-	0.4	[-]

One can observe on the stress-strain curves (Fig. 2.3.9) that t can affect the peak and residual stresses sensitively while the yield strain is not modified. As t increases, both the peak and residual stresses increase, but the difference between the peak and residual stresses decreases too. When $t=0.3$ kPa, the stress-strain curve (blue line) presents a stress drop characteristic of strain softening. This phenomenon tends to diminish when t increases as the plastic behavior tends to be perfectly plastic (no stress drop or strain softening) when $t=10$ kPa.

Fig. 2.3.10 shows the failure envelope defined at the interparticle scale (see section 2.1.3). The horizontal line represents the maximum admissible shear stress (related to the interparticle cohesion). The vertical line represents the maximum admissible tensile stress. When the limiting shear force is reached, the bond will carry on at the interparticle contact and follow the failure envelope up to the point where the maximum admissible tensile force is reached (and where the bond will break as presented in section 2.1.3). When the ratio of the maximum normal force to the maximum shear force is small (this ratio is directly related to the ratio t/c and is equal to 0.3 here when $t=0.3$ kPa and $c=1$ kPa), the material presents a brittle behavior when healing is not considered. When healing is considered, the behavior is not brittle and associated to wide shear zones. When the ratio t/c is relatively big (the ratio is equal to 10 when $t=10$ kPa in Fig. 2.3.10), more indentation is required to develop the shear zone and large amount of damage/fracturing can be observed in front of the indenter. When healing is considered, the behavior is more ductile. This characteristic appears

clearly in the stress strain curve (Fig. 2.3.9) as strain softening becomes smaller as t increases.

In the plane-strain indentation tests (Fig. 2.3.11), one can see that the deformation changes from failure associated to wide shear zones (Fig. 2.3.11A) to localized faulting (Fig. 2.3.11B, C, D and E) and then to failure with less shear zones (Fig. 2.3.11F) when t increases. When t is small, the behavior is similar to what can be observed in weak granular materials with diffusion deformation associated to small offset faults. When t is large, the shear zone formation requires more indentation amount.

When $t=0.3$ kPa, the offset along the strike-slip fault is relatively small (Fig. 2.3.11A). The shear zone is not well localized. The extruded sub-block does not rotate at all. When $t=0.5$ kPa (Fig. 2.3.11B), the strike-slip is more open and the strike-slip fault extrudes the sub-block away from the main block. An open zone can be observed at the end of the strike-slip fault but the sub-block does not rotate.

When $t=1$ kPa (Fig. 2.3.11C), a first strike-slip fault propagates toward the east edge and isolates a sub-block which tends to rotate clockwise. This rotation induces the opening of the zone located at the end of the first strike-slip fault. A second strike-slip fault nucleates from the left corner of the indenter. It does not propagate to the east edge but rather stops inside the model. The offset along the second strike-slip fault induces an open zone at the end of the first fault and there are two small open zones at the end of the second strike-slip fault.

When $t=1.2$ and 1.5 kPa (Fig. 2.3.11D, E), the deformation pattern is very similar to the case with $t=1$ kPa. Comparing the three open zones caused by the first strike-slip fault, we can identify that their area decreases as t increases, and that the rotation of the extruded block decreases as well.

When $t>10$ kPa (Fig. 2.3.11F), the first strike-slip fault extrudes the sub-block without rotation and opens the zone at the end of the strike-slip fault.

To sum up, t influences the indentation amount to form the first strike-slip fault, the open zone at the end of the strike-slip fault, and the rotation of the sub-block.

Fig. 2.3.9. Stress-strain curves obtained from uniaxial compression tests performed with different values of t .

Fig. 2.3.10. Evolution of the contact yield envelope: when the tensile strength t changes from 0.3 to 10 kPa, the yield envelope translates toward the left.

<p>A, $t=0.3$ kPa Step $44 \cdot 10^4$ indentatio n amount 8.88 m</p>		<p>B, $t=0.5$ kPa Step $44 \cdot 10^4$ indentatio n amount 8.88 m</p>	
<p>C, $t=1$ kPa Step $44 \cdot 10^4$ indentatio n amount 8.9 m</p>		<p>D, $t=1.2$ kPa Step $44 \cdot 10^4$ indentatio n amount 8.86 m</p>	
<p>E, $t=1.5$ kPa Step $44 \cdot 10^4$ indentatio n amount 8.84 m</p>		<p>F, $t=10$ kPa Step $44 \cdot 10^4$ indentatio n amount 8.85 m</p>	

Fig. 2.3.11. Deformation patterns obtained from plane-strain indentation tests performed for different values of t .

2.3.5 Cohesion (c)

The cohesion c corresponds to the maximum admissible shear stress at the interparticle scale. c should thus play a key role in shear zone or strike-slip fault formation and propagation. The set of parameters used for this study is given in Table 2.3.5.

Table 2.3.5 Parameters for testing the cohesion (c)

Parameter	Symbol	Value	Unit
Number of elements	-	100,000	-
Mean element radius	R	0.123	[m]
Ratio of largest to smallest element	-	1.86	[-]
Interaction range coefficient	γ_{int}	1	[-]
Particles' elastic modulus	E	1	[MPa]
Tangential stiffness coefficient	a	0.01	[-]
Tensile strength	t	1	[kPa]
Cohesion	c	0.05, 0.1, 0.3, 0.5, 1, 2, 5, 8, and 10	[kPa]
Weakening coefficient	s	10	[-]
Shortening rate of indenter	v	0.01	[m/s]
Damping coefficient	D_a	0.4	[-]
Time interval coefficient	-	0.4	[-]

With the set of parameters chosen here, one can observe that the peak and residual stresses change with the value assigned to c , but the slope of the curve at the elastic stage is unchanged. When c increases from 0.05 kPa to 1 kPa, the peak and residual stresses increase dramatically. The increase of residual stress is however smaller than the increase of the peak stress. In general, the stress-strain curve changes from ideal elastic-plastic to strain-softening as c increases. However, when c varies from 1 kPa to 10 kPa, the peak and residual stresses do not change. This is because the

tensile strength t of the bonds is equal to 1 kPa: the bonds reach the maximum admissible tensile force before the maximum admissible shear force. To sum up, with this set of parameters, c affects the stress-strain curve when it is smaller than t . If c is greater than t , it does not affect the material strength. In the following section, we also investigate the influence of the cohesion in relation with the tensile strength.

The influence of c on the contact yield envelope is shown on Fig. 2.3.13 while its influence on the mechanical response of the model is shown on Fig. 2.3.12. When the ratio t/c is big (e.g. 20 when the $c=0.05$ kPa) the deformation of the material presents a diffusion behavior. When the ratio t/c is small (e.g. 0.1 when $c=10$ kPa), the material shows strain softening. But, because of few shear yield contacts, failure occurs through the formation of a wide shear zone (the first shear zone in the second column in Fig. 2.3.14).

The effect of c was also investigated for the plane-strain indentation models (Fig. 2.3.14). We compare the deformation of models at the indentation amount about 6 m (step 30×10^4) in the second column of Fig. 2.3.14, and the further deformation with even more indentation amount in the third column of Fig. 2.3.14 (more than 10 m). When $c=0.05$ kPa (Fig. 2.3.14A) or 0.1 kPa (Fig. 2.3.14B), which are much smaller than t , the deformation is diffuse without any large fault generation. In Fig. 2.3.14A, the behavior of model 1 is too diffuse to generate any visible big fault. The rotation of the deformed part of model at the right side is 25° counterclockwise for a penetration of the indenter of 6.02 m. For further indentation (10.63 m) (and for this particular set of parameters), there is still no clear strike-slip faulting, no clockwise rotation, and no extruded sub-block as well. For model 2 (Fig. 2.3.14B), there is only a short strike-slip fault which does not propagate toward the edge of the model and thus does not form

the first sub-block after a penetration of 6.02 m. The rotation of the right deformed part of the model is 20° counterclockwise, which is smaller than the one obtained with model 1. For further penetration of the indenter (10.63 m), the deformation is still diffuse without any apparent fault or extruded sub-block.

When $c = 0.3$ kPa (model 3), the first strike-slip fault is more clear than for models 1 and 2 (Fig. 2.3.14C). When the indenter's penetration is 6.02m, the fault is long enough to propagate toward the edge of the model and to generate a sub-block, which extrudes from the main model. The rotation of this extruded sub-block is 4° counterclockwise. For further indentation (10.24 m), a second strike-slip fault nucleates and propagates toward the edge to form additional sub-blocks.

When $c = 0.5$ kPa (model 4), the first strike-slip occurs after an indentation of 6.03 m and propagates toward the edge (Fig. 2.3.14D). Moreover, a small open zone forms at the easternmost extremity of the fault. This strike-slip fault and the open zone induce the rotation of the isolate sub-block extruded from the main block. The rotation of the sub-block is 9° clockwise. Please note that the rotation becomes clockwise whereas it was counterclockwise for models 1, 2, and 3. When the indenter further penetrates inside the model (10.44 m), a second strike-slip fault forms and propagates toward the edge of the model, and generates a second sub-block. One can also observe a small open zone at the end of the second strike-slip fault.

The first strike-slip fault can be observed also when $c = 1$ kPa (model 5, Fig. 2.3.14E) for an indentation of 6.04 m. This strike-slip fault propagates and obviously opens the zone at the end of the fault. This open zone is relatively bigger than the one obtained with model 4. The fault extrudes the first sub-block, and the sub-block rotates

10° clockwise. When the indenter goes further up to 10.11 m, a second strike-slip fault forms and propagates to generate an open zone at the end of the second strike-slip fault.

For model 6 where $c=2$ kPa, the open zone is smaller than the one obtained with model 5 (Fig. 2.3.14F) and the rotation of the sub-block is 2° clockwise. When the indenter penetrates 10.67 m, the second strike-slip fault starts.

For model 7 with $c=5$ kPa, the first strike-slip fault nucleates and propagates to form the first sub-block which rotates 8° counterclockwise (Fig. 2.3.14G). The size of the open zone caused by the first strike-slip fault is even smaller than with model 6. When the indenter penetrates 14.08 m, the second strike-slip fault occurs and propagates to form the second sub-block.

For model 8 with $c=10$ kPa, the first strike-slip fault has not propagated toward the edge after the indenter has penetrated 6.02 m, (Fig. 2.3.14H). The potential sub-block rotates 9° counterclockwise. There is no apparent open zone related to the first strike-slip fault. When the indenter goes further to 12.06 m, the second strike-slip fault generates and propagates.

To sum up, c controls the faulting pattern. The faulting pattern influences strike-slip faulting, the formation of the sub-block, the generation of the open zone, and the rotation of the sub-block. When $c \leq 0.1$ kPa, no large strike-slip faulting occurs, therefore, no sub-block, and no open zone can be generated. When $c \geq 0.3$ Pa, two large strike-slip faults form. These two strike-slip faults extrude two sub-blocks away from the main block but the size of the open zones induced by strike-slip faulting is

different. The open zone increases as c increases from 0.3 kPa, to 0.5 kPa, and to 1 kPa. When c increases from 1 kPa, to 2 kPa, to 5 kPa, and further to 10 kPa, the open zone decreases. The rotation of the isolate or potential sub-blocks also depends on c . When c is equal to 0.05, 0.1, 0.3, 0.5, 1, 2, or 5, 10 kPa, the rotation is equal respectively to -25° , -20° , -4° , 9° , 10° , 2° , -8° , and -9° . Thus, with the same indentation amount, the rotation of the sub-block can either increase or decrease depending on the value of c (Fig. 2.3.15). As soon as c is close to 1 kPa, which corresponds to the value of the tensile strength t , the rotation is maximum.

From the physical point of view, c controls the shear deformation (from diffuse failure to localized shear faulting). In other words, depending on the value of c , the deformation pattern of the model can be diffuse or localized associated to strike-slip faulting. c strongly impacts also the length and number of induced faults, the formation of the open zone at its extremity, the size of the open zone, the extrusion of the sub-block as well as its rotation.

Fig. 2.3.12. Stress-strain curves obtained from uniaxial compression tests performed with different values of c .

Fig. 2.3.13. Evolution of the contact yield envelope when cohesion changes from 0.05 to 10 kPa, the curve of yield envelope translates toward the top.

	Step $30 \cdot 10^4$	Further indentation until the second strike-slip fault forms
A, model 1 $c=0.05$ kPa	Penetration amount 6.02 m Counterclockwise rotation 25°	Step $53 \cdot 10^4$ penetration amount 10.63 m
B, model 2 $c=0.1$ kPa	Penetration amount 6.02 m Counterclockwise rotation 20°	Step $53 \cdot 10^4$ penetration amount 10.63 m
C, model 3 $c=0.3$ kPa	Penetration amount 6.02 m	Step $51 \cdot 10^4$ penetration amount 10.24 m

	Counterclockwise rotation 4°
D, model 4 $c=0.5$ kPa	Penetration amount 6.02 m Clockwise rotation 9°	Step $52 \cdot 10^4$ penetration amount 10.44 m
E, model 5 $c=1$ kPa	Penetration amount 6.04 m Clockwise rotation 10°	Step $50 \cdot 10^4$ penetration amount 10.11 m
F, model 6 $c=2$ kPa	Penetration amount 6.025 m Clockwise rotation 2°	Step $53 \cdot 10^4$ penetration amount 10.67 m
G, model 7 $c=5$ kPa	Penetration amount 6.02 m	Step $70 \cdot 10^4$ penetration amount 14.08 m

Fig. 2.3.14. Deformation patterns obtained from plane-strain indentation tests

performed for different values of c .

Fig. 2.3.15. Relationship between the rotation of the first sub-block (potential or isolated) and the cohesion c (for an indentation of about 6.02 m).

2.3.6 Tensile strength and cohesion value (tc)

In the previous sections, the effects of tensile strength and cohesion were investigated independently but some cross-correlated effects could be found. We explore thus here the influence of the two components combined together. We applied different values to both t and c (keeping $c=t=tc$) on the two models (cube and plane-strain indentation models). The set of parameters used for this study is given in Table 2.3.6.

Table 2.3.6 Parameters for testing the tensile strength and cohesion (tc)

Parameter	Symbol	Value	Unit
Number of elements	-	100,000	-
Mean element radius	R	0.123	[m]
Ratio of largest to smallest element	-	1.86	[-]
Interaction range coefficient	γ_{int}	1	[-]
Particles' elastic modulus	E	1	[MPa]
Tangential stiffness coefficient	a	0.01	[-]
Tensile strength and cohesion	t and c	0.1, 0.5, 1, 2, 5 and 10	[kPa]
Weakening coefficient	s	10	[-]
Shortening rate of indenter	v	0.01	[m/s]
Damping coefficient	D_a	0.4	[-]
Time interval coefficient	-	0.4	[-]

Using this set of parameters, the stress-strain curves (Fig. 2.3.16) show that the tc value affects both the peak and residual stresses. Both values increase with tc .

The influence of tc on the contact yield envelope is shown on Fig. 2.3.17. Because $t=c$, the ratio of the maximum admissible tensile strength to maximum shear strength keeps constant. When tc is small (e.g. $tc=0.1$ kPa), the interparticle bonds can be broken with relatively small deformation. Failure is associated to the formation of a

wide shear zone and little offset along the shear zone. When tc is big (e.g. $tc=10$ kPa), the shear zone formation requires more indentation amount.

In Fig. 2.3.18, the second and third columns show respectively the first strike-slip formation and the further deformation of the plane-strain indentation models for different values of tc . For $tc=0.1$ kPa, the first strike-slip fault forms after a penetration of 1.41 m of the indenter (Fig. 2.3.18A). When the indentation is equal to 10.1 m, two strike-slip faults tend to isolate two sub-blocks away from the main block. Nonetheless, the strike-slip faults are neither localized nor clear. The rotation of the first sub-block is 18° clockwise.

For $tc=0.5$ kPa, the first strike-slip fault forms after 1.6 m of penetration (Fig. 2.3.18B) which is more than in the previous case. Further deformation leads to the formation of two strike-slip faults that propagate when the indentation is of about 10.09 m. Open zones also form at the end of the strike-slip faults. The rotation of the first sub-block is 25° clockwise. This rotation is bigger than the one obtained in the previous case.

When $tc=1$ kPa, the first strike fault forms after the indenter has penetrated 2.6 m into the model (Fig. 2.3.18C). When the indenter reaches 10.11 m, it produces two strike-slip faults and generates two open zones at the end of these two strike-slip faults. The rotation of the first sub-block is 28° clockwise.

For $tc=2$ kPa, the first strike-slip fault forms after a penetration of 4 m (Fig. 2.3.18D). When the penetration is equal to 10.04 m, an open zone forms at the end of the fault but no other strike-slip fault forms. The strike-slip fault extrudes a sub-block

which rotates 6° clockwise. Comparing the cases with $tc=1$ kPa to this case ($tc=2$ kPa), the deformation of the model changes from two sub-blocks extrusion to only one sub-block extrusion for the same indentation amount of 10.1 m.

When $tc=5$ kPa, the nucleation of the first strike-slip fault occurs when the indentation amount is equal to 4.41 m (Fig. 2.3.18E). When the indenter has penetrated 10.05 m inside the model, the firstly generated strike-slip fault induces the rotation of the extruded sub-block by 12° clockwise. As for $tc=2$ kPa, only one strike-slip fault and one sub-block are generated with the indentation amount 10.05 m.

When $tc=10$ kPa, the deformation pattern is very similar to the one obtained with $tc=2$ kPa and $tc=5$ kPa (Fig. 2.3.18F). The indentation needed to form the first strike-slip fault is 4.42 m. When the indentation has reached 10.07 m, the rotation of the first sub-block is 9° clockwise. Only one strike-slip fault and one sub-block could be generated with the indentation of 10.07 m.

To form the first strike-slip fault, the required indentation amount gradually increases from 1.41 m to 4.42 m as tc increases from 0.1 kPa to 10 kPa (Fig. 2.3.19). Because of this increase of the required indentation to form the first strike-slip fault, the further deformation of the model leads to two strike-slip faults and two sub-blocks for $tc=0.1, 0.5$ and 1 kPa and to one strike-slip fault and one sub-block for $tc=2, 5$ and 10 kPa (for the same penetration as illustrated in the third column of Fig. 2.3.18). Therefore, if we need less penetration to deform the model, tc should be small, and vice-versa. A point we should pay attention on is the rotation of the induced sub-block. It always rotates clockwise, whatever the value of tc . The amount of rotation may be

different though, since the rotation is also affected by the fault pattern. Thus, t_c affects the amount of rotation but does not change the character of this rotation (clockwise).

Fig. 2.3.16. Stress-strain curves obtained from uniaxial compression tests performed with different values of $t_c = c = t$

Fig. 2.3.17. Evolution of the contact yield envelopes when t_c changes from 0.1 to 10: the curve of yield envelope translates toward the northwest side.

	The first fault occurs	The final step
A, $t_c=0.1$ kPa	Step $7 \cdot 10^4$ Indentation amount 1.41 m	Step $50 \cdot 10^4$ Indentation amount 10.1 m Rotate 18° clockwise
B, $t_c=0.5$ kPa	Step $8 \cdot 10^4$ Indentation amount 1.6 m	Step $50 \cdot 10^4$ Indentation amount 10.09 m Rotate 25° clockwise
C, $t_c=1$ kPa	Step $13 \cdot 10^4$ Indentation amount 2.6 m	Step $50 \cdot 10^4$ Indentation amount 10.11 m Rotate 28° clockwise
D, $t_c=2$ kPa	Step $20 \cdot 10^4$ Indentation amount 4 m	Step $50 \cdot 10^4$ Indentation amount 10.04 m

Fig. 2.3.18. Deformation patterns obtained from plane-strain indentation tests performed for different values of $tc=c=t$.

Fig. 2.3.19. Relationship between tensile strength and cohesion ($t_c=c=t$) and the indentation amount required to form the first strike-slip fault: the higher the tensile strength and cohesion are, the more indentation amount is required.

2.3.7 Tangential stiffness coefficient (a)

In the previous section (section 2.1.3), the a value corresponds to the ratio between the normal and the tangential stiffnesses defined at the contact between two interacting particles $\frac{K_s}{K_n}$. In this section, our purpose is to identify the value of a that could allow the model to deform with similar faulting pattern as the ones observed in nature. The a value is related to shear force calculation in the model. Shear force controls the fault propagation. From the literature, a is related to the Poisson's ratio ν_p of the simulated material. However, several different expressions have been proposed to express the relationship between a and ν_p in DEM models depending on the material considered. As you can see below, equations (Eq. 2.3.1 to 2.3.6) show the non-unicity of this relationship:

$$a1 = \frac{K_s}{K_n} = \frac{(1 - 3\nu_p)}{(1 + \nu_p)} \quad (2.3.1)$$

to model layered rock material (Griffiths and Mustoe, 2001; Buechler et al., 2013);

$$a2 = \frac{K_s}{K_n} = \frac{1 - 4v_p}{1 + v_p} \quad (2.3.2)$$

for brittle materials such as concrete or rock (Kuhl et al., 2001; Šmilauer, 2010);

$$a3 = \frac{K_s}{K_n} = 1 - 4v_p \quad (2.3.3)$$

to study rock and concrete behavior (Kusano et al., 1992; Camborde et al., 2000; Griffiths and Mustoe, 2001);

$$a4 = \frac{K_s}{K_n} = \frac{1 - 4v_p}{(1 + 2v_p)} \quad (2.3.4)$$

for elastic material by [Zhang et al., 2014];

$$a5 = \frac{K_s}{K_n} = \frac{2(1 - v_p)}{2 - v_p} \quad (2.3.5)$$

to simulate the elastic behavior of isotropic particulate materials by [Fleischmann et al., 2013; Mindlin and Deresiewicz, 1953; Tomas, 2001] and also suitable for the contact built between spheres and boundaries (Johnson and Johnson, 1987; Dwyer-Joyce and Gonzalez-Valadez, 2004);

$$a6 = \frac{K_s}{K_n} = \frac{0.71(1 - v_p)}{2 - v_p} \quad (2.3.6)$$

for the contact built between spheres (Yoshioka and Scholz, 1989; Nagy, 1992; Dwyer-Joyce and Gonzalez-Valadez, 2004). The relationships are shown in Fig. 2.3.20. Some researchers mentioned that the coordination number, which is determined by the interaction range coefficient, also influences the relationship between a and v_p (Gu and Yang, 2013). However, the Poisson's ratio v_p of the lithosphere also ranges between 0.2 to 0.5 (e.g. (Clarke and Silver, 1993; Christensen, 1996; Williams and Garnero, 1996; Chevrot and van der Hilst, 2000)) for elastic to incompressible materials respectively. Nonetheless, from the six curves based on the above equations (Fig. 2.3.20), the tendency is the same: the smaller a is, the greater the Poisson's ratio is. To some extent, this trend between a and the Poisson's ratio will help us adjust the a

value. In the modeling, we could obtain a suitable a value to make the faulting pattern of the model comparable to that of the lithosphere.

Using the parameter setting shown in Table 2.3.7, we could produce the stress-strain curves for uniaxial compression (Fig. 2.3.21). The stress-strain curves illustrate that a affects the peak stress, residual stress, the slope of the curve at the elastic stage and the yield strain (upper limit of the purely elastic deformation). When a increases, the plastic behavior of the material changes from diffuse to little strain softening, and then to more strain softening, and further to much more strain softening which may be close to fissuring.

Finally, we used the same parameter setting (Table 2.3.7) to conduct a total of 12 plane-strain indentation models (Fig. 2.3.22) which covers a values from 0.001 to 0.3, in order to analyze the fault pattern.

The effect of a on the deformation pattern is shown for a penetration amount of about 10 m (except the last one where it is equal to 0.76 m). As a increases, the deformation pattern changes from diffuse to one strike-slip fault, and then to two strike-slip faults, and further to open cracking. For $a=0.001$, the shear forces at the interparticle scale are very small. Thus, the shear forces will never reach the maximum admissible value (defined by the cohesion c) and failure is thus controlled by the normal component (tensile strength t). The pattern of deformation for such small value of a is diffuse. Even though the indentation amount is 10.05m, no strike-slip faults can be observed. In addition, the rotation of the right side of the model is 12° counterclockwise.

When $a=0.004$, one strike-slip fault forms for an indentation amount of 10.07 m (Fig. 2.3.22B). The rotation of the sub-block isolated by the fault is 9° counterclockwise. With $a=0.005$ and for an indentation amount of 10.08 m, the strike-slip faulting is much more significant (Fig. 2.3.22C) but the sub-block just translates eastward without any rotation. When $a=0.007$, the strike-slip fault forms for an indentation amount of 10.09 m (in Fig. 2.3.22D) and the sub-block extruded by the fault rotates 4° counterclockwise.

For $a=0.008$, two long strike-slip faults separate two sub-blocks from the main block for an indentation amount of 10.1 m (Fig. 2.3.22E). The rotation of the first sub-block is 11° clockwise. For $a=0.01$, faulting occurs for an indentation of 10.11 m (Fig. 2.3.22F). The deformation localizes to form two main large strike-slip faults. The first sub-block caused by the first strike-slip fault rotates 28° clockwise. For $a=0.02$, two strike-slip faults form for an indentation of 10.11 m but the rotation of the first sub-block is 21° clockwise (Fig. 2.3.22G). If $a=0.05$, two strike-slip faults form for an indentation of 9.97 m (Fig. 2.3.22H). The first sub-block rotates 31° clockwise. If a is equal to 0.08, 0.09, and 0.1 (Figs. 2.3.22 I, J and K), the rotations of the first sub-block are 29° , 11° , and 4° respectively with the indentation amount 9.92 m, 9.9 m and 9.89 m. All models show the formation of two strike-slip faults, and the angle between the first strike-slip fault and the front of the indenter is relatively bigger than in previous models with lower values of a . When $a=0.3$, an open crack (fissure) forms in the medium without any strike-slip faulting (Fig. 2.3.22L).

To sum up, the smaller a is, the more diffuse the deformation is. The deformation varies from diffuse to strike-slip faulting, and then to fissuring as a increases. The bigger a is, the more brittle the material is and the bigger the angle

between the first strike-slip fault and the front of the indenter becomes. As a increases, the first sub-block rotation changes from counterclockwise to clockwise rotation and to no rotation. The changes in the rotation of the first sub-block (or right edge) with a is summarized in Fig. 2.3.23. As a increases, the rotation of the first sub-block changes from counterclockwise when $a < 0.005$ to clockwise when $a > 0.005$. Then when $a > 0.005$, the rotation of the subblock first increases up to 30° when $a = 0.05$ and then decreases down to 0° when $a = 0.3$. At the interparticle scale, a influences the tangential force. In the plane-strain indentation models, a does not only play an important role on the generation of the strike-slip faults and on the angle between the strike-slip fault and the front of the indenter, but it also dramatically influences the rotation of the first sub-block.

Fig. 2.3.20. Relationships between stiffness coefficient a and Poisson's ratio v_p [Buechler et al., 2013; Camborde et al., 2000; Dwyer-Joyce and Gonzalez-Valadez, 2004; Fleischmann et al., 2013; Griffiths and Mustoe, 2001; Johnson and Johnson, 1987; Kuhl et al., 2001; Kusano et al., 1992; Mindlin and Deresiewicz, 1953; Šmilauer,

2010; Tomas, 2001; Tschoegl *et al.*, 2002; Yoshioka and Scholz, 1989; Zhang *et al.*, 2014].

Table 2.3.7 Parameters for testing the Tangential stiffness coefficient (a)

Parameter	Symbol	Value	Unit
Number of elements	-	100,000	-
Mean element radius	R	0.123	[m]
Ratio of largest to smallest element	-	1.86	[-]
Interaction range coefficient	γ_{int}	1	[-]
Particles' elastic modulus	E	1	[MPa]
Tangential stiffness coefficient	a	0.001, 0.004, 0.005, 0.007, 0.008, 0.01, 0.02, 0.05, 0.08, 0.09, 0.1, and 0.3	[-]
Tensile strength and cohesion	t and c	1	[kPa]
Weakening coefficient	s	10	[-]
Shortening rate of indenter	v	0.01	[m/s]
Damping coefficient	D_a	0.4	[-]
Time interval coefficient	-	0.4	[-]

Fig. 2.3.21. Stress-strain curves obtained from uniaxial compression tests performed with different values of a .

Fig. 2.3.22. Deformation patterns obtained from plane-strain indentation tests

performed for different values of a .

Fig. 2.3.23. Relationship between the stiffness coefficient a and the rotation of the first sub-block (potential or isolated) for an indentation of 10 m.

2.3.8 The shortening rate (ν)

We test 8 different values of the shortening rate for a given set of the model parameters. The set of parameters used for this study is given in Table 2.3.8.

Table 2.3.8 Parameters for testing the shortening rate

Parameter	Symbol	Value	Unit
Number of elements	-	100,000	-
Mean element radius	R	0.123	[m]
Ratio of largest to smallest element	-	1.86	[-]

Interaction range coefficient	γ_{int}	1	[-]
Particles' elastic modulus	E	1	[MPa]
Tangential stiffness coefficient	a	0.01	[-]
Tensile strength and cohesion	t and c	1	[kPa]
Weakening coefficient	s	10	[-]
Shortening rate of indenter	v	0.001, 0.005, 0.008, 0.01, 0.02, 0.03, 0.04, 0.05, and 0.1	[m/s]
Damping coefficient	D_a	0.4	[-]
Time interval coefficient	-	0.4	[-]

As shown in Fig. 2.3.24, the plastic behavior of the simulated material evolves with the increase of the shortening rate. In particular, strain softening decreases with the increase of the shortening rate further up to strain hardening. When the shortening rate is less than 0.01, the difference between the stress-strain curves is relatively small. When the shortening rate is greater than 0.01, the difference between the stress strain curves is significant as inertial (dynamic) effects come into play (these effects come from the explicit numerical scheme). In the plane-strain indentation model, the deformation evolves from fissuring, to faulting, and then to diffuse based on the fault pattern with the increase of v (Fig. 2.3.25). When the shortening rate is small, the strike-slip fault tends to form at a high angle from the front of the indenter (Fig. 2.3.25A, B, and C). This deformation corresponds to a brittle behavior. As the shortening rate increases, the angle between the first strike-slip fault and the front of the indenter decreases from 60° to 55° when the indentation amount is about 2.6 m. For further penetration, the angles can be more easily identified. When the shortening rate is equal to 0.01 or 0.02, the angle between the strike-slip fault and the front of the indenter is 45° (Fig. 2.3.25D and E). This fault pattern is similar to the perfect plastic shear fault, which is common in nature. The deformation is mainly due to shear faulting. The further deformation shows this character even clearly. With the true shear

fault pattern for the further indentation, the model is deformed with two strike-slip faults and two open zones generated by the two faults. When the shortening rate is 0.03, 0.04 or 0.05, (models 6, 7 and 8), the angle of the strike-slip fault from the front of the indenter is smaller than 45° (Fig. 2.3.25F, G and H). If the shortening rate is even higher, no shear fault can be identified and the deformation of the model is totally diffuse (model 9, Fig. 2.3.25I).

To sum up, as the shortening rate increases, the deformation pattern evolves from relatively strong brittle faulting to shear faulting and then to diffuse mode. The angle between the strike-slip fault and the front of the indenter decreases from 60° (relatively strong brittle behavior) to 45° (true shear failure), and then values even smaller than 45° (more diffuse), and further to no faulting (totally diffuse).

Fig. 2.3.24. Stress-strain curves obtained from uniaxial compression tests performed with different values of the shortening rate.

	Step $13 \cdot 10^4$ first fault	Further deformation
A, shortening-model 1 $\nu=0.001$	Indentation amount 2.61 m The angle between the first strike-slip fault and the front of the indenter is 60°
B, shortening-model 2 $\nu=0.005$	Indentation amount 2.61 m The angle between the first strike-slip fault and the front of the indenter is 56°	Step 26 Indentation amount 5.22 m
C, shortening-model 3 $\nu=0.008$	Indentation amount 2.6 m The angle between the first strike-slip fault and the front of the indenter is 55°	Step 36 Indentation amount 7.22 m
D, shortening-model 4 $\nu=0.01$	Indentation amount 2.61 m The angle between the first strike-slip fault and the front of the indenter is 45°	Step 50 Indentation amount 10.11 m
E, shortening-model 5 $\nu=0.02$	Indentation amount 2.59 m The angle between the first strike-slip fault and the front of the indenter is 45°	Step 46 Indentation amount 9.29 m
F, shortening-model 6 $\nu=0.03$	Indentation amount 2.58 m The angle between the first strike-slip fault and the front of the indenter is 43°	Step 50 Indentation amount 10.12 m
G, shortening-model 7 $\nu=0.04$	Indentation amount 2.57 m The angle between the first strike-slip fault and the front of the indenter is 43°	Step 41 Indentation amount 8.26 m

Fig. 2.3.25. Deformation patterns obtained from plane-strain indentation tests performed for different values of the shortening rate ν : from strong brittle behavior to faulting and then to diffuse mode.

2.3.9 Result stability test

At end, we test the stability of the modeling results. We re-run the model, using the same parameter setting in the following table and the same packing.

Table 2.3.8 Parameters for testing the stability of modeling

Parameter	Symbol	Value	Unit
Number of elements	-	100,000	-
Mean element radius	R	0.123	[m]
Ratio of largest to smallest element	-	1.86	[-]
Interaction range coefficient	γ_{int}	1	[-]
Particles' elastic modulus	E	1	[MPa]
Tangential stiffness	a	0.01	[-]

coefficient			
Tensile strength and cohesion	t and c	0.5	[kPa]
Weakening coefficient	s	20	[-]
Shortening rate of indenter	v	0.01	[m/s]
Damping coefficient	D_a	0.4	[-]
Time interval coefficient	-	0.4	[-]

We compare these two modeling results at step 42×10^4 . Even though there is a little different between the models (Fig. 2.3.26), the difference is negligible. Generally, there is no obvious difference between the models. Thus the results are stable.

Fig. 2.3.26. Deformation patterns obtained from plane-strain indentation tests performed when we run the model two times

To sum up, we choose the following set of parameters to be the reference: $\gamma_{int}=1$, elastic modulus=1 MPa, $a=0.01$, tensile strength=1 kPa, cohesion=1 kPa, $s=10$, the shortening rate is 10^{-2} m/s, and total healing when the spherical elements re-contact together.

2.4 Validation

Though the calibration described in the previous section, we choose the parameter settings described in Table 2.4.1.

Table 2.4.1 Parameters for validation

Parameter	Symbol	Value	Unit
Number of elements	-	100,000	-
Mean element radius	R	0.123	[m]
Ratio of largest to smallest element	-	1.86	[-]
Interaction range coefficient	γ_{int}	1	[-]
Particles' elastic modulus	E	1	[MPa]
Tangential stiffness coefficient	a	0.01	[-]
Tensile strength	t	1	[kPa]
Cohesion	c	1	[kPa]
Weakening coefficient	s	10	[-]
Shortening rate of indenter	v	0.01	[m/s]
Damping coefficient	D_a	0.4	[-]
Time interval coefficient	-	0.4	[-]

We use the model with this set of parameters in order to compare its predictions to the experimental results obtained with the plasticine analogous model used by (Peltzer and Tapponnier, 1988). For that matter, we analyze the fault patterns, rotation of the first isolated block, and the displacement field and try to relate them to the field observations.

2.4.1 Fault pattern comparison

We set up a numerical model with boundary conditions similar to the plasticine model (Fig. 2.4.1) in order to compare the fault pattern. In particular, the plasticine model enabled to reproduce the two main large strike-slip faults (the Red River and Altyn Tagh faults), as well as the two extruded and rotated sub-blocks (the Sundaland and South China blocks) (Fig. 2.4.2 and Fig. 1.1). The two sub-blocks are generated

and extruded one-by-one due to the progressive propagation of the two strike-slip faults. The plasticine model allowed to identify two phases: firstly, the first strike-slip fault S1 (the Red River fault) forms and propagates, and then extrude the first sub-block B1 (Sundaland) which finally rotates clockwise towards the southeast; secondly, the second strike-slip fault S2 (the Altyn Tagh fault) formed and developed, and the S2 worked together with the first strike-slip fault to produce and extrude the second sub-block B2 (South China).

The geometry of the numerical model is similar to the plasticine model and the values of their dimension are also similar, but with different scales. The unit of the numerical model is meter, and 1 meter represents 500 km in nature. The unit of the plasticine model is centimeter and 1 centimeter represents 500 km in nature (Fig. 2.4.1). The width of the simulated zone in the numerical model along W-E direction is equivalent to the one of the plasticine model. Nonetheless, the numerical model is longer along the N-S direction in order to avoid boundary effects.

The 2D numerical model produce similar results to the ones obtained with the plasticine. All the different features observed in the plasticine experiment can be reproduced with the 2D numerical model. These features include the strike-slip faulting, open zone forming, and sub-block extruding. For instance, as illustrated in Fig. 2.4.2A, for the same amount of indentation, the right-lateral fault D1 forms from the right corner of the indenter toward the northwest. The amount of indentation corresponds to 600 km in reality for both cases (1.2 m in the numerical model and 1.16 cm in the plasticine model). We observe that the left-lateral strike-slip fault S1 generates from the left corner of the indenter and propagates toward the northeast (Fig. 2.4.2B which is at stage 10 of the numerical simulation). This fault is analogous to the

S1 fault at stage 12 in the plasticine experiment. In Fig. 2.4.2C (stage 13 of the numerical simulation), S1 propagates toward the east edge, which generates the first sub-block B1. This sub-block is extruded toward the east, translated by S1. The deformation of the numerical model in this stage is analogous to that of the plasticine experiment at stage 17. In Fig. 2.4.2D (stage 19 of the numerical simulation), S1 continues propagating, and forms an open zone at its east extremity which leads to the rotation of B1 toward the southeast. This opening zone at the extremity of S1 and the rotating of B1 are comparable to the ones obtained in the plasticine experiment at stage 22. Fig. 2.4.2E shows at the stage 25 in the numerical model, the opening zone and the rotation of B1 continue deforming when compared to the stage 22. With the rotation of the B1, the open zone becomes bigger and bigger. At some point (stage 25), the second strike-slip fault S2 starts to form at the left corner of the indenter. At stage 27 of the plasticine experiment, the open zone at the extremity of S1 and the rotation of B1 both increase, and S2 starts to generate. In Fig. 2.4.2F (stage 31 of the numerical simulation), S2 does not develop as much as in the plasticine experiment (stage 32). In Fig. 2.4.2G (stage 37 of the numerical simulation), S2 does develop in the numerical model, and the sub-block B2 is almost formed. The size of S2 and B2 are comparable to those obtained in the plasticine experiment at stage 37. In Fig. 2.4.2H (stage 43 of the numerical simulation), an open zone forms at the extremity of S2 whereas S2 propagates toward the edge to form sub-block B2 in the plasticine experiment (stage 42). To sum up, except the fact that S2 does not propagate toward the edge of the numerical model, all other deformation features predicted by the numerical model are very similar to the ones observed in the plasticine model.

Fig. 2.4.1. Boundary conditions and geometries of (left) the numerical model and (right) the plasticine model.

C

19

D

25

E

F

37

G

43

H

Fig. 2.4.2. Comparison of the fault patterns observed in (left) the numerical model and (right) the plasticine model; the fault in red means active at the current stage, and the fault in orange means inactive at the current stage.

2.4.2 Comparison of the rotation of sub-block B1

In order to further assess the pertinence of the numerical predictions, we tracked the rotation paths of the four selected points D', E', F', and G' in the numerical model (Fig. 2.4.3) and compared them to the points D, E, F and G in the plasticine model. Based on the rotation paths, the rotation poles P' and P can be obtained respectively for the numerical model and for the physical model. One can note that the radius of rotation of B1 is bigger in the numerical model than in the plasticine model. On the other hand, the rotation paths in the numerical model are in very good agreement with the ones obtained in the plasticine. Overall, the numerical predictions are consistent with the experiment.

Fig. 2.4.3. Comparison of the rotation poles and paths obtained in (left) the numerical model and (right) the plasticine model.

To go further in the comparison, we recorded the rotation of Point G' (Red line Fig. 2.4.4) and compared the rotation of G in the plasticine model. B1 rotates faster in the plasticine model than in the numerical model. At the beginning of the indenter penetration, the rotation of B1 in the numerical model is bigger than that in the plasticine model. Once the indentation amount is greater than 3.5, the rotation of B1 in the numerical model is smaller than in the plasticine model. At the end of the simulation, the rotation of B1 in the plasticine model is still increasing, while it rotates backward in the numerical model (Fig. 2.4.3/Left and Fig. 2.4.4). In addition, the amount of the rotation decreases in the last stage. Overall, the rotation trend of B1 is similar in both models.

Fig. 2.4.4. Rotation of the sub-block B1 as a function of the indenter penetration for both the numerical and the plasticine models

2.4.3 Displacement field comparison

We compare here the displacement field of the numerical model to the one observed in the plasticine model (Fig. 2.4.5). In Fig. 2.4.5A (from stage 6 to 10), the triangular zone in front of the indenter mainly moves to the north, and the right corner of the model dominantly moves to the east. The displacement of the right corner progressively increases from the north to the south. These two features were also observed in the plasticine model. From stage 13 to 19 (Fig. 2.4.5B), because the first

sub-block B1 has isolated from the model, the displacement distribution of the triangular zone which is located at the right-bottom corner generally increases from the south to the north, which is opposite of what was observed in the previous stages (Fig. 2.4.5A). Because of the increase of the displacement from the south to the north of B1, B1 rotates toward the southeast. For the area in front of the indenter, the direction of displacement changes from the north to the north-northeast. These features obtained with the numerical model are congruent with the ones observed in the plasticine model. From stage 25 to 31 (Fig. 2.4.5C), B1 is extruded and rotates away from the main block. The second sub-block B2 starts to move toward the east. Again, these features are in agreement with the results observed in the plasticine model. From stage 37 to 43 (Fig. 2.4.5D), B1 continues its movement and rotates clockwise while the B2 moves toward the east and rotates counterclockwise. The movements of these two sub-blocks are in accordance with the deformations observed in the plasticine model. Once again, the predictions of the numerical model are consistent with the ones observed in the plasticine model.

In addition, we analyzed the x-component (W-E direction) and y-component (N-S direction) of the displacement field separately. Doing so, we could identify the location of the different faults developing in the model including the right-lateral faults (such as D1 and D2) which start from the right corner of the indenter. These right-lateral faults cannot be observed based solely on the total displacement field (Fig. 2.4.5 or Fig 2.4.6 left column).

From stage 6 to 10 (Fig. 2.4.6A), the total displacement field shows that the whole triangular zone (B1+T1), which is bounded by S1 at the right corner of the model, has ~1 m of displacement. According to the x-component of the displacement

field, the area B1 located on the right corner of the model shows more movement along the x direction than the zone T1 located at the front of the indenter. On the contrary, according to the y-component displacement field, T1 shows more movement along the y direction than B1. Thus, the offset along D1 at the right corner of the indenter can be identified. From stage 13 to 19 (Fig. 2.4.6B), the zone (B1+T1) at the bottom-right part of the model moves faster along S1 than other parts in the model. The displacement of this zone varies from ~1.2 to ~2.7 m. In details, B1 translates more than T1 along the x direction. The movement along the x direction on the area B1 increases from the south to the north. This gradient of displacement tends to rotate B1 toward the southeast. T1 suffers very small displacement along the x direction, but it moves significantly along the y direction (about 1.4 m). From stage 25 to 31 (Fig. 2.4.6C), the region (in green) moves faster than other parts of the model. In this region, B1 moves faster than T2 along the x direction. In B1, the movement along the x direction is similar to the movement of the whole block, so no rotation occurs. T2 moves faster than B1 along the y direction, with few movements along the x direction. From stage 37 to 43 (Fig. 2.4.6D), B2 is generated by the strike-slip fault S2. B2 moves to the east mainly. T2 dominantly moves to the north. The north part of B1 moves to the east. This movement of B1 decreases from the north to the south, which tends to rotate B1 toward the southeast. Thus, the rotation of B1 can be decomposed in two phases: after the strike-slip fault S1 has formed, and after the strike-slip fault S2 has formed.

2D numerical model

Displacement (m)
2.7 2.4 1.8 1.2 0.6 0

A

6-10

B

13-19

Plasticine model

8-12

17-22

Fig. 2.4.5. The displacement fields observed in the numerical model (left) and the plasticine model (right).

Fig. 2.4.6. Resultant, x-component and y-component of the displacement field observed in the numerical model: A, stage 6-10; B, stage 13-19; C, stage 25-31; D, stage 37-43.

2.4.4 Comparison of the numerical predictions to the field

In order to further validate the numerical model, we compared the numerical predictions to the geological observations. Firstly, the scaled total indentation amount

(~4000 km) is comparable to the reality (2000-3000 km (Molnar and Tapponnier, 1975; Peltzer and Tapponnier, 1988)). Secondly, the open zone at the end of the second strike-slip fault is consistent with the Shanxi graben. Thirdly, when the second block extrudes, the first strike-slip fault S1 changes from left-lateral to right-lateral slip, which is congruent with the change sense of the Red-river fault.

2.4.4.1 Indentation amount

Using the plasticine model, Peltzer and Tapponnier 1988 could reproduce the indentation amount (total 3350 km) (Fig. 2.4.2) observed in reality (total 2000-3000 km) (Molnar and Tapponnier, 1975; Peltzer and Tapponnier, 1988). In this section, we compare the indentation amount observed in the plasticine experiments with the one obtained in the numerical simulations. In Table 2.4.1, we list the scaled amounts of indentation for each representative stage of the numerical and plasticine models and plot them in Fig. 2.4.7. For each stage, the indentation amount in the numerical model is bigger than the one obtained with the plasticine model. During the first three stages, these two amounts are very close. After stage 3, some discrepancies start to appear. The total indentation amount recorded in the numerical model is about 30% bigger than the one recorded in the plasticine model. One has to note that the mechanical properties of the material play an important role in these differences and have thus to be pointed out. Firstly, the plasticine is an anisotropic material as it is made of layers with interfaces between layers that act as planes of weakness (Peltzer and Tapponnier, 1988). On the contrary, the distribution of bonds in the numerical model is homogenous and isotropic. At the beginning, the indentation amounts of these two models are close and similar fault patterns develop in the models. With further indentation, the deformation of the medium is more and more influenced by the mechanical properties. For the anisotropic material (plasticine model), the fault tends

to follow the weak joint along W-E direction to some extent. So the model deforms along the faults with relatively less indentation amount. For the isotropic material (numerical model), without any weak planes along the W-E direction, even though the fault pattern is similar, the model deforms for relatively more indentation amount.

Table 2.4.1. The amount of indentation for each representative stage (km)

	A	B	C	D	E	F	G	H
Numerical model	600	1000	1300	1905	2515	3125	3745	4350
Plasticine model	580	855	1270	1685	2100	2520	2935	3350

Fig. 2.4.7. Illustration of the indentation amounts and the stages of the plasticine and numerical models

2.4.4.2 Shanxi graben simulation

In Fig. 2.4.2, the fault patterns observed in both the numerical and plasticine models are compared. We can note that the fault pattern of the second strike-slip fault S2 is different in these two models. In the numerical model (Fig. 2.4.8 Left), S2 creates a tensional basin at the right extremity of the fault, instead of developing to the edge as in the plasticine model. This particular feature is analogous to the Shanxi graben system (Fig. 2.4.8 Right). At the extremity of S2, which represents the Altyn-tagh fault, two main open cracks are generated. The relatively small sub-block between these two open cracks is rotated. These features are consistent with the ordos basin bounded by the two normal faults which are Weihe-Shanxi graben in the east and Yinchuan normal fault in the west.

Fig. 2.4.8. Comparison of normal faults in the numerical model (left) and the graben systems around the Ordos (right).

2.4.5 Right-lateral motion along the Red River fault

We zoom in the displacement field in the last stage of the deformation (Fig. 2.4.5D) in order to see more precisely the movement of the deformed areas. The first strike-slip fault (the red dash line in Fig. 2.4.9) corresponds to the Red River fault. From the displacement field, one can observe that the north side of the Red River is moving faster to the east than the south side. The arrows on the south side of the Red River fault shows that this side is mainly moving to the south. Thus, the movement along the Red River seems to be potentially right-lateral. This character is consistent with the popular interpretation that the Red-river fault was left-lateral fault and it changed to be right-lateral moving since about ~15 Ma (Lacassin et al., 1993; Leloup et al., 1993; Leloup et al., 1995; Lacassin et al., 1997; Lacassin et al., 1998; Leloup et al., 2001; Replumaz et al., 2001).

Fig. 2.4.9. Movement along the first strike-slip fault

2.4.6 Conclusion

We compared the numerical predictions of our DEM model to the experimental observations obtained with the plasticine. In the simulations, we could observe the two sub-blocks (B1 and B2) phase extrusion and rotation. We could also identify the two main strike-slip faults (S1 and S2) nucleation and propagation. We could obtain all the

main features that were observed in the plasticine experiment in terms of fault pattern, rotation of the sub-blocks and displacement field. Furthermore, we compared our results to the geological map. We could simulate the basin zone of Weihe-Shanxi graben and the Ordos block. The change of sense of the Red-river fault (from left-lateral to right-lateral motion) could also be identified in the numerical model. Thus, using the numerical model, most important first-order horizontal deformation in the Asian plate can be simulated. However, the vertical deformation of the Asian plate including the thrust faulting and the Qinghai-Tibet plateau generation could not be investigated using this 2D model. In the next Chapter, the 3D numerical modeling of the India-Asia collision will be considered.

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Chapter 3 3D case application to the India-Asia collision zone

The Indian plate collided with the Asian plate approximately 50 million years ago (e.g. (Molnar and Tapponnier, 1975; Tapponnier et al., 2001; Replumaz and Tapponnier, 2003; Replumaz et al., 2004; Replumaz et al., 2010a; Replumaz et al., 2010b)). This collision generated the highest mountains (the Himalayas) and broadest plateau on the Earth, together with some of the world's largest strike-slip faults (Tapponnier and Molnar, 1976; Peltzer, 1988; Replumaz et al., 2004; Wittlinger et al., 2004). The evolution of the collision zone in the last 50 million years remains an outstanding problem. Meyer et al. (1998) and Tapponnier et al. (2001) proposed a discrete growth model of the plateau: the QingHai-Tibet plateau would have been rising step by step from south to north. This Plateau is now bounded by three distinct mountains connected with three large strike-slip faults. It is composed of several sub-plateaus also bounded by distinct thrusts. A stepwise model of topographic uplift has also been suggested by Liu Jing et. al. (2008).

Previous studies have attempted to explain the horizontal deformation using experimental plasticine models [e.g. (Peltzer and Tapponnier, 1988)]. Such models could simulate the growth of the main strike-slip faults and other horizontal deformation of geological features. But, evidently, this 2D modeling approach cannot simulate the vertical deformation and is not scaled dynamically with gravity. To address both plane-strain and thickening occur simultaneously,

the 3D plasticine model (Peltzer, 1988) has attempted to use centrifuge to achieve correct scaling with respect to gravity stresses. But, the centrifuged equipment cannot allow fixed boundary condition to the west and north, which influences the deformation of model concentrated at the east part of the model as what we know in the Asian plate. More recently, finite element modelling, whether the vertically averaged “thin viscous sheet” or the decoupled weaker “lower crustal flow” classes of models, mimicked the lateral continual growth of the Tibetan plateau [e.g. (England and Houseman, 1986; England and Molnar, 1997; Royden et al., 1997; Shen et al., 2001; Cook and Royden, 2008)]. These models show neither the real progress of the plateau, nor narrow zones with large offsets, as observed in geology. Some other recent modeling attempts focus on the overall simulation of the large-scale India-Asia continental collisions (Capitanio and Replumaz, 2013; Replumaz et al., 2014), but cannot address localized offsets along large strike-slip, thrust or normal faults.

Here, we use the discrete element method to construct a numerical model which simulates both horizontal and vertical deformation during collision. In the discrete element method, the material is assumed to be an assembly of lots of spheres linked together by normal and shear forces. The normal and shear forces are calculated based on the stiffness and the displacement between the contacting spheres.

We begin with a description of the main large-scale geological features in the Asian plate that must be considered in any serious modeling attempt. We then follow by scaling of the modelling approach and by assessing the boundary

influences between the Indian and Asian plates. We present the long-term, large-scale 3D numerical models performed to simulate the India-Asia collision progress, describe the observation from the model, and compare in map view and section the modeling results to the faults and plateau observed. Finally, we discuss the alternation of horizontal and vertical deformation in the model and in India-Asia collision zone.

3.1 Main Tertiary-Quaternary geological features

The collision between the Indian and Asian continental plates causes crustal thickening, strike-slip faulting, and rifting. The description of the main geological features (Fig. 3.1.1, 3.1.2, and 3.1.3) in the Asian plate may be summarized as follows:

1. Around the Qinghai-Tibet plateau

Besides the Qinghai-Tibet plateau generation, the horizontal deformation (such as strike-slip faulting in China) around the plateau also plays an important role. Almost half of the shortening amount since 50 Ma in the India-Asia collision is absorbed by these large (>1000 km long) fault zones (e.g. (Tapponnier et al., 1986; Peltzer and Tapponnier, 1988)).

Red River fault (labeled S1 in reference to models)

The Red River fault, a 1500 km-long left-lateral strike-slip fault located in Yunnan, South China, extends from Southeastern Tibet to the South China Sea (Leloup et al., 1995). The Red River fault switched to be right-lateral slipping in the Pliocene (Allen et al., 1984; Yang and Besse, 1993). Its left-lateral movement was very large, with amount of slip ranging from a minimum of ~ 500 km to

perhaps 700 ± 200 km [e.g. (Leloup et al., 1995)]. That movement was coeval with the opening of the South China Sea from ~ 33 Ma to 15 Ma, at a rate of 3 to 4 cm/yr. It contributed to move Sundaland southwards relative to the South China block (Fig. 3.1.1). The dextral movement of at least 25 km along the Red River fault (Replumaz et al., 2001; Replumaz and Tapponnier, 2003), started before 5 Ma with a the slip rate of <4 cm/yr (Tapponnier et al., 1990; Leloup et al., 2001; Replumaz et al., 2001; Replumaz and Tapponnier, 2003).

Fig. 3.1.1. Schematic map of mainly horizontal deformation of eastern Asia. Heavy lines, major faults or plate boundaries. Large open arrow represent qualitatively major block motions respective to Siberia since Eocene. Smaller solid arrow indicate directions of extension after (Tapponnier et al., 1982; Tapponnier et al., 1986; Peltzer, 1988; Peltzer and Tapponnier, 1988).

Fig. 3.1.2. Topography and principal active faults of Tibet and adjacent regions. Bold lines are faults that slip at 5 mm/year or more. Bold numbers indicate rates where known. Thin lines, slower slipping faults. Dashed thin lines, inferred faults. Dotted lines, recent or growing folds. White arrows indicate motions of India, central Tibet, northeasternmost Tibet, and Sichuan relative to Siberia after (Tapponnier et al., 2001).

Fig. 3.1.3. Simplified map of major tectonic boundaries and Tertiary faults in Tibet. Noted: WDF, Wangding fault; NTH, Nantinghe fault; MLF, Menglian fault; MXF, Mengxing fault; MCF, Mae Chan fault (Tapponnier et al., 2001).

Altyn Tagh fault (S2 in reference to models)

The Altyn Tagh fault (Tapponnier and Molnar, 1977) is left-lateral, starting from the east side of the India and Asia collision zone (Fig. 3.1.1, 3.1.2 and 3.1.3). It is the longest strike-slip fault in Asia (~1800 km). Studies of the slip rate from sinistral offsets of glacial or fluvial features suggest rates between a maximum of about 2.7 ± 0.7 cm/yr in the last 120 ka to the west (Peltzer et al., 1989; Mériaux et al., 2004), 1.8 ± 0.4 cm/yr in the last 10 ka in the central part (Mériaux et al., 2005) and perhaps about 1 cm/yr or less (4 ± 2 mm/yr) to the east, in the Gansu province (Meyer et al., 1996). The total sinistral offset could reach maximum of ~500 km (Peltzer and Tapponnier, 1988), although perhaps not all during the Tertiary.

Tien Shan, Altai and Baykal zone (S3 in reference to models)

The Tien Shan is known as the longest and highest mountain belt of central Asia (Fig. 3.1.1). The average convergence rate across the Tien Shan is $\sim 1.0 \pm 0.3$ mm/yr, and its average maximum elevation is about 4,000 m [e.g. (Avouac et al., 1993)]. The tectonics of the Tien Shan, Altai and Baykal zone are a consequence of a gradual change with distance in the average state of stress away from India (mainly thrust faulting in the Tien Shan, strike-slip faulting in the Altai and Mongolia, and mainly normal faulting in the Baykal region) (Tapponnier and Molnar, 1976, 1977, 1979; Chen et al., 1991). Based on the observation of the strike-slip faulting component in these broad regions, shortening appears to be absorbed by conjugate faulting between the Altai and Baykal [e.g. (Tapponnier and Molnar, 1979)]. The ~ 15 Ma onset of deformation in the Tien Shan, Altai and Baykal zone might be a distant consequence of the end of Indochina's escape (Avouac et al., 1993).

NE-SW trending faults on the Shan-Thai plateau

On the Shan-Thai plateau (Fig. 3.1.3), the India-Asia collision generated a series of short strike-slip faults, among which the Wanding fault, Nantinghe fault, Menglian fault, Mengxing fault and the Mae Chan fault. The left-lateral offsets along these faults are from few kilometers to tens of kilometers (Lacassin et al., 1998; Wang et al., 2014). However, most of them were right-lateral slipping before 6 Ma. Thereafter, the slip sense changed from right lateral to left-lateral, and this inversion is almost concurrent with the slip change of the Red River fault (Lacassin et al., 1998).

Tertiary movements of Southeast Asian blocks (extrusion and rotation) (B1 and B2 in reference to models)

First phase: Sundaland block extrusion and rotation

The Sundaland block (Fig. 3.1.1) includes Thailand, Indochina, the Sunda Shelf, Peninsular Malaysia and Sumatra, Borneo, Burma East of the central lowlands, Yunnan South of the Red River Fault (e.g. (Hutchinson, 1982)) and possibly parts of SouthWest Tibet (e.g. (Tapponnier et al., 1986)). After an orogeny in the Triassic, the Jurassic and Cretaceous were periods of relative tectonic quiescence. During the Middle Cretaceous, thick continental sandstones were deposited on the stable Khorat Plateau. That plateau stable depositional sequence is analogous to that in the Sichuan Basin. Previous studies show geological evidences to support that the Sundaland block is extruded and rotated with the Red-River propagation towards the southeast (Yang and Besse, 1993).

Second phase: South-China block extrusion

The South-China block comprises mostly the Precambrian Yangze Craton, the Sichuan Basin and the edges of surrounding mountains. This block is bounded by the Red River-Ailao Shan fault, the subduction zone along Taiwan, and the eastern China Sea margin (Fig. 3.1.1) (e.g. (Tapponnier et al., 1982)). The geological evidence suggests that the South-China block is now extruded towards the east between the Red River-Ailao Shan and Qinling Shan.

Andaman Sea

The Andaman Sea is located between the western edge of Sundaland (Myanmar, Thailand and Malaysia) and the Andaman-Nicobar Arc along the India-Asia plate boundary (Fig. 3.1.1). In the south, it terminates in the Mergui and Sumatra Basin. The Andaman basin is a complex, multiphase basin that opened in several phases as a pull-apart between large, roughly north-south strike-slip faults (the Sumatran and West Andaman faults in the south-west and the Sagaing fault in the north). It is not a “classic” back-arc basin in any way (e.g. (Peltzer and Tapponnier, 1988)).

South China Sea

The South China Sea formed in relation with Oligomiocene left-lateral displacements along the Red River-Ailao Shan, Wang Chao, and Three Pagodas fault zones [e.g. (Tapponnier et al., 1986; Peltzer and Tapponnier, 1988; Briais et al., 1993)] (Fig. 3.1.1). The opening of the South China Sea was initially documented by Taylor and Hayes (1980, 1983). The more recent interpretation of a larger set of magnetic anomalies by Briais et. al (1993) showed that the opening of the sea was coeval and compatible with left-lateral movements and clockwise rotations of slices of Sundaland (including Borneo) relative to South China along the Red River, Wang Chao, and Three Pagodas faults. The major sea floor spreading events in the South China Sea occurred between 33 and 16 Ma (Briais et al., 1993; Leloup et al., 2001). This is the period during which major deformation of continental southeast Asia occurred as a result of the collision between India and Asia.

Shanxi graben (junction area of S2 and D2 in the model)

The Shanxi graben system, which completely surrounds the Ordos plateau or block (Fig. 3.1.1) is located in the central part of north China. It is bounded by the Haiyuan fault to the southwest, and composed of the Yinchuan graben in the northwest, the Weihe graben in the south and the Fenhe graben in the east and whole Hohhot-Baotu graben in the north. The overall kinematic around this isolated Ordos block properly include anticlockwise rotation, and such rotation may be driven by the propagation and present motion along faults in the Qinling Shan that are continuation of the Haiyuan fault. Such fault takes up the eastward motion of South China relative to North China, but do not extend far west of the Ordos. At a smaller scale, this is similar to the South China Sea been generated as the large pull-apart by the Red River-Ailao Shan left-lateral fault. The Yinchuan and Fenhe normal faults are general perpendicular to the Qinling fault.

2. In the Qinghai-Tibet plateau

The generation of the Qinghai-Tibet plateau and of the geological features within the plateau is central to understand the mechanisms of the India-Asia collision. The numerical modeling results must thus be compared to the deformation and rise of the plateau.

Karakorum fault and Zangbo suture

In the Southwest part of Tibet, the Zangbo suture zone is overlapped by a large strike-slip shear zone: the Karakorum fault, with at least 350 km of right-lateral offset in the Oligo-Miocene, since about 25 Ma (Lacassin et al., 2004) (Fig. 3.1.2, 3.1.3 and 3.1.4). This fault zone is located north of the Himalayan range. Toward the east, right-lateral strike-slip movement may continue in part along the Zangbo suture zone (Tapponnier et al., 1986).

Bangong Nujiang suture

North of the Karakorum and Zangbo zone, the Bangong Nujiang suture is now sheared by the system of “en echelon” right-lateral strike-slip fault (Fig. 3.1.2, 3.1.3 and 3.1.4) (Armijo et al., 1986; Armijo et al., 1989; Tapponnier et al., 2001). Additional thrust faulting along the suture may have contributed to the generation of the south Qinghai-Tibet plateau, while, the dextral strike slip motion along this suture may contribute to the eastward extrusion of Tibet.

Tanggula Shan range

North and closely parallel to the Bangong Nujiang suture, and located in the center of the Tibetan plateau (Fig. 3.1.2, 3.1.3 and 3.1.4) (e.g. (Tapponnier et al., 2001)), is the Tanggula Shan range, which was uplifted by thrust movement. To the east, the range may connect with other mountains (such Ailao Shan) near the Red-River fault.

Fenghuo shan, Jinsha suture, and Xianshuihe fault

The Fenghuo Shan, Jinsha suture, and Xianshuihe fault are located north of the Tanggula Shan fault (Fig. 3.1.2, 3.1.3 and 3.1.4) (e.g. (Tapponnier et al., 2001)). As along the Tanggula Shan, Tertiary thrusting along these ranges may have contributed to the uplift of the Tibetan plateau, whereas strike-slip along the Xianshuihe fault contributes to extrude the central plateau towards the east and south.

Qiman-Kunlun shan and Kunlun fault

North of the Fenghuo Shan, Jinsha suture and Xianshuihe fault, the Qiman-Kunlun Shan and Kunlun fault form yet another sinistral strike-slip/thrust pair analogues to the previous one (Fig. 3.1.2, 3.1.3 and 3.1.4). Thrust faults south of the Kunlun range are similar to thrusts south of the Altyn Tagh fault. The left-lateral strike slip offset between the eastern and western Kunlun ranges is about 500-600 km. Previous studies suggest that the offset along the sinistral Kunlun fault occurred in the last 14 to 24 million years [e.g. (Tapponnier et al., 2001)]. Although the cumulative offset along the Kunlun fault remains debatable, the consensus is that it reaches or exceeds 100 km.

Qilian Shan and Haiyuan fault

The Qilian Shan and Haiyuan fault, at the northern edge of the Qinghai-Tibet plateau, and are clearly associated with the Altyn-Tagh fault (Fig. 3.1.2, 3.1.3 and 3.1.4). The Haiyuan fault may be thought of as a splay of the Altyn-Tagh fault. The formation of the Qilian Shan may be thus be understood as a push-up between these two faults. Along the Qilian Shan, the two main components of deformation are ESE left-lateral faulting, and NNE shortening. The dominant left-lateral strike-slip movement along the Haiyuan fault may be transferred across the Liupan Shan further Southeast to the Qinling fault. Gaudemer (Gaudemer et al., 1995) concluded that shortening in the eastern Qilian Shan and left slip on the Haiyuan Fault probably started at the same time, in the late Miocene. The possible cumulative shortening on the Qilian Shan thrusts is at least 25 km. The left-lateral offset of the Haiyuan fault is at least 40 km, and probably on order of the offset of the Huang-He (~90km) (Gaudemer et al., 1995).

The Jiali fault and Nianqing Tanggula Shan

The Jiali fault and Nianqing Tanggula Shan are located in southeast Tibet, north of Lhasa (Fig. 3.1.2 and 3.1.3). The Nianqing Tanggula Shan is a NE-SW trending mountain range a~200 km long and ~80 km NW of Lhasa. Its southeast flank is bounded by an active left-lateral strike-slip fault, the western Jiali fault (Armijo et al., 1989). The Jiali fault has been interpreted to extend far southeastwards between the Tibetan plateau and the Shan-Thai Plateaus. These would imply previous studies imply that the Nainqing Tanggula and the Red River shear zones may have been connected by the Jiali fault. The formation and age of the Jiali fault and Nianqing Tanggula Shan range have long been debated, with no conclusive agreement. The range is surprisingly oriented NE-SW and is one of the highest mountain range inside the Tibetan plateau with two summits higher than 7000 m. One earlier study inferred that shear occurred along the Nianqing Tanggula range as earlier as 40 Ma (Tapponnier et al., 1986). Others suggested that episodic Miocene magmatism was active from ~24 to 8 Ma (ages that span >10 m.y) (Kapp et al., 2005). Some interpret the emplacement and crystallization of the Nianqing Tanggula granite to be about 18 Ma (Liu et al., 2004), and possibly from ~18 to 12 Ma (Lee et al., 2003). Other studies demonstrated rapid cooling along the shear zone at about 8 Ma (*Harrison et al., 1992; Pan and Kidd, 1992; Harrison et al., 1995*). Therefore, the precise age of the Nianqing Tanggula Shan and earlier Jiali fault is still debatable, and this fault may have been active from 40 to 8 Ma. Its origin also remains debatable.

In summary, all the faults described above appear to be related to the formation of Qinghai-Tibet plateau. Following the “oblique stepwise rise and growth of the Tibet plateau” interpretation proposed by Tapponnier et al. (2001), the entire plateau may have been built in three steps, progressively from south to north. Soon after the India-Asia collision, the Banggong and Jinsha sutures would have been reactivated as mantle megathrusts, in the Eocene (Roger et al., 2000). The first sub-plateau would thus be bounded by the Zangbo and Jinsha sutures. At that time, the Tanggula Shan and Fenguo Shan ranges, and the Red River and Xianshuihe shear zones, would have bounded that first plateau (Fig. 3.1.3), with coeval transpressive folding and thrusting along the southern and northern edges, and infilling of the intervening southeastern Tibetan basins in the Lhasa block, Qiangtang, Yunnan, and the Shan-Thai plateau. Later, the second sub-plateau, in central Qinghai province bounded by the Tanggula/Jinsha, Kunlun and Lungmen Shan ranges, would have grown in the Oligocene/Miocene. The third phase of growth and rise is still in progress. This last sub-plateau is limited by, and is growing coevally with, the Kunlun and Alyn-Tagh faults, Qilian Shan, and Haiyuan Fault since the late Miocene.

Fig. 3.1.4. Schematic lithospheric section of Cenozoic evolution of Himalaya-Tibet orogeny. (Meyer et al., 1998; Tapponnier et al., 2001)

3.2 Model set up and mechanical behavior

Using the code we have tested, with calibrated and validated parameters, and based on the plane-strain indentation geometry, we set up a 3D model to simulate the deformation in the Asian plate caused by the India-Asia collision.

3.2.1 Model setting up

The 3D model (Fig. 3.2.1) is built similar to the plane-strain indentation model. Similar to the plane-strain indentation model horizontally, the 3D model is 22.5 m wide, 30 m long. This model size is big enough to avoid the boundary effect and also small enough to satisfy the calculation ability of the computer. The northern and western boundaries are rigid (no displacement) and smooth (no friction). The eastern and southern boundaries are free except along the indentation contact. The indenter is 5 m wide, and 12.5m far from the left corner and 5 m far from the right corner. The indenter penetrates with a fixed velocity into the model. Vertically, the thickness of the model is 0.25 m thick. Unlike the plane-strain indentation model in which two rigid plates prevent any vertical deformation, the top and bottom surfaces of the model are free. Gravity and buoyancy forces are taken into account in the 3D simulation. Scaling will be discussed later. For the buoyancy force imposed to the model, the densities of the modeled lithosphere and modeled mantle are 2260 and 2580 kg/m³ respectively. In order to simulate the deformation of the lithosphere, which is floating on the asthenosphere, the key point here is to keep the ratio of the densities of the lithosphere and mantle at 7/8, which is consistent with related densities in nature. The gravity and buoyancy force work together to make the lithosphere stable there.

The model is composed of 300,000 spherical elements with a mean spherical radius of 42 mm, uniformly distributed between maximum radius of 54.6 mm, and a minimum radius of 29.4 mm. The ratio between maximum and minimum is 1.86 (about 2). The spherical elements are randomly located.

The parameters of the 3D model are given based on the plane-strain indentation model too. Similar to the plane-strain indentation model, the physical parameters are as shown in Table 3.2.1.

Table 3.2.1 Parameters for validation

Parameter	Symbol	Value	Unit
Number of elements	-	300,000	-
Mean element radius	R	42	[mm]
Ratio of largest to smallest element	-	1.86	[-]
Interaction range coefficient	γ_{int}	1.15	[-]
Particles' elastic modulus	E	1	[MPa]
Tangential stiffness coefficient	a	0.008	[-]
Tensile strength	t	1	[kPa]
Cohesion	c	1	[kPa]
Weakening coefficient	s	70	[-]
Shortening rate of indenter	v	0.01	[m/s]
Damping coefficient	D_a	0.4	[-]
Time interval coefficient	-	0.4	[-]
Gravitational acceleration	g	10	[m/s ²]

The gravitational acceleration will be changed when we test its effect. Complete healing is also applied on this model. The strength of the contact between the spheres and the indenter is tested from 0 to 0.2 kPa, then to 0.5kPa and then further to 1 kPa which is the same as the contact between spheres.

The elastic modulus, tensile strength, cohesion, shortening rate, damping value, and time interval are the same in both the plane-strain indentation and 3D models. There are more degrees of freedom here than in the plane-strain indentation model. For 3D models, we need to adjust the parameters including the interaction range coefficient γ_{int} , the weakening coefficient s value, and the tangential stiffness coefficient a value, which are related to the types of failure behavior (ductile or brittle). The interaction range coefficient could be tuned when testing the strength of the interface between the model and the indenter. In order to decrease the dynamic energy of the whole system, the weakening coefficient s value, which is affected much by the freedom degree of the system, need to be higher than in the plane-strain indentation model. The tangential stiffness coefficient a value also need to be tuned, but it is still in the range which we tested for the rotation of the sub-blocks in the plane-strain model.

(a) Top view of the model

(b) North-South cross section of the model

Fig. 3.2.1. Dimension and boundary conditions of the 3D model: (a) top view, 22.5 m wide, and 30 m height. The width of the indenter is 5m, 12.5m far from the left corner and 5m far from the right corner. Similar to the plane-strain indentation model, two rigid plates are placed at the west and north of the model. The east and south of the model are free except the indentation contact edge. The indentation with a fixed velocity penetrates into the model. (b) north-south cross section of the model with 0.25 m thick.

3.2.2 Mechanical behavior of the model

Before simulating the India-Asia collision zone, we need to understand the mechanical behavior of the model. As mentioned in the previous chapter, the mechanical behavior is essential to determine the model deformation pattern. We test the 3D model with the failure pattern and stress-strain curves as was done for the validation of 2D models. We take a sample (5m*5m*0.25m) from the 3D model to test the model with a uniaxial compression loading (Fig. 3.2.2), in order to obtain the strength of the intact model and of the re-healed fault. The geometry of the model in length and width is the same as the 2D model in the last chapter, except for the thickness. The boundary of the compression test is also the same as in the 2D model.

The uniaxial compression test generally provides the strength of the model and the failure pattern indicates the re-healed fault. The model strength is about 1700 Pa (Fig. 3.2.2). The angle of the fault is approximate 45°. After failure, the residual strength of the model is about 700 Pa, which is suggested to be mainly borne by the

fault. Therefore the strength of the fault may be 700 Pa. However, as the shear strength of the model and fault influences the fault propagation, we set up a direct shear test to quantify the shear strength of the model.

The model has the same spherical element packing as in the uniaxial compression test. The boundary condition of the test is illustrated in Fig. 3.2.3. The model is constrained by two plates in the front and at the back to simulate the plane-strain deformation. One half of the model is fixed in the black box, and the other half is constrained in the blue box which moves at a given velocity (equivalent to the loading rate of the indenter in the indentation model).

The direct shear test results show that the deformation of the model is almost totally absorbed by the fault propagation (Fig. 3.2.3 b-e). From the stress strain curve (Fig. 3.2.3f), the peak stress corresponds to the shear strength of the intact model, which is about 800 Pa. The residual stress of the model corresponds to the shear strength of the fault, which is about 600 Pa.

Therefore, when we determine the strength of the entire model during its deformation (intact model and fault deforming together), it is feasible to take the strength of the model with 1 kPa.

(C)

(D)

(E)

Fig. 3.2.2. Uniaxial compression test: A)-D): Fault propagation, the failure pattern with the compression loading. E) stress-strain curve of the uniaxial compression loading, letters on the curve refer to deformation pattern from A) to D).

Fig. 3.2.3. Direct shear test: a) Initial state of the model with boundaries. b)-e), Fault propagation, all deformation of the model by the shear is concentrated on the slip along the fault. (f) Stress strain curve of the direct shear test, the peak stress is the

strength of the intact model, the residual stress (the roughly flat stress after the peak stress) corresponds to the strength of the fault.

3.3 Scaling and gravitational acceleration value (g) effect

Scaling is very important for both the analogy experimental modeling and numerical simulation. For the modeling of the geological structures, Hubbert discussed the theory of scaling law for models decades ago [Hubbert, 1937]. The scaling equations and laws are used for many models of geological structures deformation [Buiter et al., 2006; Hubbert, 1951; Ramberg, 1967; Ranalli and Murphy, 1987; Rey and Houseman, 2006; Schellart, 2000] and volcano eruption modeling [Merle and Borgia, 1996]. Here, we scale our models with respect to gravity.

3.3.1 Scaling

From the static equilibrium formula, the equation is as follows:

$$\Sigma F_i = 0$$

The sum of all three components of force is equal to 0. The equation is along x direction as follow:

$$\begin{aligned} \left(\sigma_x + \frac{\delta \sigma_x}{\delta x} dx \right) dydz - \sigma_x dydz + \left(\tau_{xy} + \frac{\delta \tau_{xy}}{\delta y} dy \right) dx dz - \tau_{xy} dx dz \\ + \left(\tau_{xz} + \frac{\delta \tau_{xz}}{\delta z} dz \right) dx dy - \tau_{xz} dx dy + X dx dy dz = 0 \end{aligned}$$

The equilibrium formula along y direction is:

$$\begin{aligned} \left(\tau_{yx} + \frac{\delta \tau_{yx}}{\delta x} dx \right) dydz - \tau_{yx} dydz + \left(\sigma_y + \frac{\delta \sigma_y}{\delta y} dy \right) dx dz - \sigma_y dx dz \\ + \left(\tau_{yz} + \frac{\delta \tau_{yz}}{\delta z} dz \right) dx dy - \tau_{yz} dx dy + Y dx dy dz = 0 \end{aligned}$$

The equation is along z direction following:

$$\begin{aligned} & \left(\tau_{zx} + \frac{\delta \tau_{zx}}{\delta x} dx \right) dydz - \tau_{zx} dydz + \left(\tau_{zy} + \frac{\delta \tau_{zy}}{\delta y} dy \right) dx dz - \tau_{zy} dx dz \\ & + \left(\sigma_z + \frac{\delta \sigma_z}{\delta z} dz \right) dx dy - \sigma_z dx dy + Z dx dy dz = 0 \end{aligned}$$

So, the above three equations are simplified with:

$$\frac{\delta \sigma_x}{\delta x} + \frac{\delta \tau_{xy}}{\delta y} + \frac{\delta \tau_{xz}}{\delta z} + X = 0$$

$$\frac{\delta \tau_{yx}}{\delta x} + \frac{\delta \sigma_y}{\delta y} + \frac{\delta \tau_{yz}}{\delta z} + Y = 0$$

$$\frac{\delta \tau_{zx}}{\delta x} + \frac{\delta \tau_{zy}}{\delta y} + \frac{\delta \sigma_z}{\delta z} + Z = 0$$

From the body forces, yz , $Z dx dy dz$, there are $X = \rho g_x$, $Y = \rho g_y$, $Z = \rho g_z$. The Einstein notation version of the above three equations is

$$\frac{\delta \sigma_{ji}}{\delta x_j} + \rho \cdot g_i = 0 \quad (3.3.1)$$

It represents the lithostatic equilibrium with $j=1, 2$, and 3 .

Using the dimension scaling law [Hubbert, 1937], we scale the model with nature. Before scaling the model, we need to address some of more relevant symbols. For the reality, the strength, displacement, density, and gravitational acceleration in the lithostatic equilibrium formula are σ_{ij} , x_j , ρ , g_i respectively, and the strength, density, gravitational acceleration and the thickness of the lithosphere are σ_c , ρ_c , g_c , h_c respectively. For the model, the strength, deformation displacement, density, and gravitational acceleration in the static equilibrium formula are σ'_{ij} , x'_j , ρ' , g'_i respectively, and the strength, density, gravitational acceleration and the thickness of the model are σ'_c , ρ'_c , g'_c , h'_c respectively.

The dimension scaling coefficient ψ , λ , δ , and γ are the ratios of the strength, length, density and acceleration of the model and nature [Hubbert, 1937]. The relation of strength, length, density and acceleration between the lithosphere and model are

$$\sigma'_{ij} = \psi \sigma_{ij}, x'_j = \lambda x_j, \rho' = \delta \rho, g'_i = \gamma g_i$$

And these coefficients also satisfy the following equations

$$\psi = \frac{\sigma'_c}{\sigma_c}; \lambda = \frac{h'_c}{h_c}; \delta = \frac{\rho'_c}{\rho_c}; \gamma = \frac{g'_c}{g_c}$$

Based on the definition of stress scaling coefficient [Hubbert, 1937], these coefficients should satisfy the equation

$$\frac{\psi}{\delta \gamma \lambda} = 1 \quad (3.3.2)$$

Then, the static equilibrium formula becomes

$$\frac{\frac{\sigma_c}{\sigma'_c} \delta \sigma'_{ij}}{\frac{h_c}{h'_c} \delta x'_j} + \frac{\rho_c}{\rho'_c} \rho' \cdot \frac{g_c}{g'_c} g'_i = 0 \quad (3.3.3)$$

$$\frac{\frac{\sigma_c}{\rho_c g_c h_c}}{\frac{\sigma'_c}{\rho'_c g'_c h'_c}} \cdot \frac{\delta \sigma'_{ij}}{\delta x'_j} + \rho' g'_i = 0 \quad (3.3.4)$$

Following the scaling rule,

$$\frac{\psi}{\delta \gamma \lambda} = \frac{\frac{\sigma_c}{\rho_c g_c h_c}}{\frac{\sigma'_c}{\rho'_c g'_c h'_c}} = 1 \quad (3.3.5)$$

It also matches to the static equilibrium formula for the model:

$$\frac{\delta \sigma'_{ij}}{\delta x'_j} + \rho' g'_i = 0 \quad (3.3.6)$$

So, the conclusion is

$$\frac{\sigma_c}{\rho_c g_c h_c} = \frac{\sigma'_c}{\rho'_c g'_c h'_c} \quad (3.3.7)$$

The ratio of the strength over the density, gravitational acceleration and the thickness of the lithosphere should be equal to that of the model. If satisfying this condition, the model is scaled with the lithosphere [Peltzer, 1988].

If we use σ_c to represent the average strength of the lithosphere and h_c as its whole thickness, the dimensionless force ratio $\frac{F_t}{F_g} = \frac{\sigma_c}{\rho_c \cdot g_c \cdot h_c}$ expresses the balance between tectonic forces and gravity induced forces [Peltzer, 1988]. If the value of this ratio is the same in nature as in the numerical model, the model will be scaled with respect to gravity.

In nature, we use the values as follows:

$\sigma_c = 5 * 10^5 kPa$, $h_c = 10^5 m$, $\rho_c = 2.8 g/cm^3$, and $g_c = 9.8 m/s^2$, using the dimensionless force ratio equation above, $\frac{F_t}{F_g} = 0.17$ for continental lithosphere.

On the other hand, $\frac{F_t'}{F_g'} = 0.35$ in our model is achieved while $\sigma_c' = 1 kPa$, $h_c' = 0.25 m$, $\rho_c' = 1.13 g/cm^3$, and $g_c' = 10 m/s^2$. This value in our model is of the same order of magnitude as the value of 0.17 obtained for the real continent.

With the scaled parameters for 3D modeling, we are therefore confident that the general deformation pattern is reasonable. But for more detailed comparison of deformation patterns, we also need to test the gravitational acceleration value used in the model.

3.3.2 Gravitational acceleration value (G) effect

In our experiments, we can test different gravitational acceleration values to see their effect on the deformation. We test the model with different modeled g values which varies from 5 to 20 m/s^2 . (“3D-Buo-thinner-model 67” in my experimental series)

All parameters for the model are the same as the model setting in the previous section. We compare the horizontal deformation in map view and vertical deformation in a cross section within the yellow zone (Fig. 3.3.1). The influence of g is clear on the deformation pattern.

With almost the same penetration amount (4.27m with $g = 5$ and 4.41m with $g = 10, 15$, and 20), the horizontal and vertical deformed shapes of the models are different. When $g = 5 \text{ m/s}^2$ (case 1), there is no large-scale strike-slip fault (Fig. 3.3.1a). The model is deformed with two small conjugate strike-slip faults making a triangle with the indenter front and a wide open zone at the apex of the triangle. For the vertical deformation, the model is maximally thickened 3.6 times the thickness of the initial model (Fig. 3.3.2a). When g is 10 m/s^2 (case 2), two large left-lateral strike-slip faults form, allowing the extrusion and rotation of two sub-blocks away from the main model (Fig. 3.3.2b). The maximum thickness of the deformed model is 3 times that of the initial model. In case 3, when the g is 15 m/s^2 , the block is also deformed with two large strike-slip faults (Fig. 3.3.1c), with larger offsets especially for the northernmost strike-slip fault. The maximum thickening amount of the model is now 2.5 (Fig. 3.3.2c). In case 4, where $g = 20 \text{ m/s}^2$, the block is again deformed with two large strike-slip faults (Fig. 3.3.1d).

The maximum thickness of the deformed block is only 2.2 times the initial thickness (Fig. 3.3.2d). To sum up, the maximum thickened model drops from 3.6 to 3 then to 2.5 and then to 2.2 times of the model initial state, as g increases from 5 to 10 then to 15 and then to 20 m/s^2 . In addition, the maximum uplift and the maximum of the root amount of the model also decrease as the G value increases (Fig. 3.3.4). Thus, the vertical deformation decreases when g increases. Since the indentation amount is almost the same, it implies that the horizontal deformation increases as g value increases. Therefore, we conclude that the vertical deformation decreases and the horizontal deformation increases if the G value increases.

Fig. 3.3.1. Initial state of the model and boundary conditions, the yellow rectangle (the position of the yellow zone is 15 m from the left corner, and 1 m width, and 15 m length) shows the cross-section zone.

Fig. 3.3.2. Illustration of horizontal strike-slip fault patterns with almost the same penetration amount and various modeled G value. When the given G value is very low (e.g. $G=5$), the collision cannot generate large strike-slip faults. If the model is scaled with respect to the given G value, it can generate two large strike-slip faults (e.g. $G=10$).

Fig. 3.3.3. Cross sections show thrust fault patterns and vertical deformations vary with different modeled G values. As the given G value increases, the thickened amount of the model decreases.

Fig. 3.3.4. Maximum of the uplift and maximum of the root vs G value; the dash lines represent the initial surface and bottom of the model respectively. Both the uplift and root amounts decline as the G value rises.

Appendix 3.3.

We also test the modeled gravitational acceleration value with another model which is smaller with fine spherical elements. For this smaller model, the size of the model is 20m*25m*0.25 m. The number of spheres is also 300,000.

From the Fig. 3.3.A1, A2, A3 and A4, the G effect on the model is the same as the effect in the above models.

Fig. 3.3.A1. Initial state, boundary conditions and dimensions. The Yellow zone shows the cross-section position. The yellow zone is located 12.5 m away from the left corner of the model, 0.04*20 m width and 0.6*25 m length.

Fig. 3.3.A2. Horizontal fault patterns with almost the same collision shortening amount vs various given G values (Step=80).

Fig. 3.3.A3. Vertical thickening patterns with the various given G values (Step=80).

Fig. 3.3.A4. Maximum of the uplift and maximum of the root vs G values; the dash lines represent the initial surface and bottom of the model respectively.

3.4 Interface strength effect in the collision zone

From geological observations and plasticine modelling, the major left-lateral faults have slipped eastwards along the front of the collision interface, apparently the Altyn Tagh fault slipped along the Himalayas [Tapponnier and Molnar, 1977]. This slip of the Altyn Tagh fault is determined by the lower friction along the interface of the Indian and Asian plates. To understand the contact mechanical behavior of the interface, we test the influence of the interface strength in our analogous models.

In the previous chapter and previous section, we have analyzed the effect of the physical parameters in the plane-strain indentation model and the gravitational acceleration effect on the model. In Peltzer and Tapponnier's paper [*Peltzer and Tapponnier*, 1988], boundary conditions have been discussed (such as the effect of free boundary on the east side). Here, we analyze the strength (including tensile strength and cohesion) between the indenter and the model, which could be related to the friction effect on the indenter.

In DEM models, we test the strength of the bond between the indenter and the model (BIM) which we built in section 3.2. The initial settings and boundary conditions are same as in the figure for the gravity value test, except the bond strength between the model and indenter. We consider four cases to test the strength of BIM: in case A, there is no tensile strength and no cohesion of BIM, in case B, the tensile strength and cohesion of BIM are one fifth of that the values of the model. In case C, tensile strength and cohesion of BIM are one half those of the model. In case D, the tensile strength and cohesion of BIM are equal to those of the model. Thus, from case A to case D, the general strength of BIM increases from 0 to 0.2 times then to 0.5 and then to 1 times that of the model inside.

The parameters used for the four models are as follows: Young's modulus = 1 MPa, tangential stiffness coefficient $\alpha = 0.008$, tensile strength = 1 kPa, cohesion = 1 kPa, weakening coefficient $s=70$, density = 1100 kg/m³, gravitational acceleration 10 m/s², and thickness of model 0.25 m, the damping value 0.4, the time interval 0.4, and the indentation speed 0.01 m/s are as in the previous section. The indentation amounts in all cases are same, which is 7.32 m after 90×10^4 steps. When the bond between the model and indenter is strong, we may need to adjust a little bit about the interaction

range coefficient γ_{int} value to avoid brittle cracking behavior. We use the γ_{int} value 1.10 for the case D and case C, 1.12 for the case B, and 1.15 for the case A. This adjustment does not influence the testing of BIM strength. For some models, we do not need to adjust this value to obtain the same effect of the BIM strength to observe the effect of the BIM strength (see in Appendix).

We measure the slip along the front of the indenter of models (Fig. 3.4.1). In case A, with no strength in the BIM, the slip amount along the front of the indenter is about 2.3 m (the width of the indenter is 5 m). In other words, the offset between the model and the front of the indenter is almost half-width of the indenter. When the strength of BIM is 0.2 times that of the inside model (case B), the slip amount along the front of the indenter decreases to 0.8 m. In cases C and D, we cannot observe any slip along the front of indenter with a penetration of 7.32 m. For higher indentation values, we obtain different slip amount between them (see in Appendix), with the slip amount in case C being bigger than in case D. Therefore, the slip in front of the model is clearly dependent on the strength of the bond between the model and indenter the stronger the BIM bond, the less slip along the front of the indenter. In nature, the slip of the Altyn Tagh fault along the front face of the collision zone could be explained with weak strength of the interface contact between the Indian and Asian continental plates.

Case A: 0

Case B: 0.2

Case C: 0.5

Case D: 1

Fig. 3.4.1. The strength of the BIM affects on the slip amount in front of the indenter. The slip amount decreases as the strength of the BIM increases. Case A has no strength between the model and indenter; the strength between the model and indenter is 0.2 and 0.5 times the model inside in Case B and Case C respectively; Case D has the same strength between the model and indenter to the model inside.

Appendix 3.4.

One more set of models is to test the interface strength effect on the slip amount of the strike slip fault along the front of the collision zone. The parameters for the following three cases are using as follows: the interaction range coefficient γ_{int} value 1.11, Young's modulus 1 MPa, the tangential stiffness coefficient a value 0.01, tensile strength 1 kPa, cohesion 1 kPa, the weakening coefficient s 60, density 1100 kg/m³, gravitational acceleration 5 m/s², and thickness of model 0.5 m, the damping value, the time interval, and the indentation speed are same (model 32 in my experiment series). The indentation amounts of all cases are same, which is 9.11 m after 90×10^4 steps.

After analyzing the slip along the front of the indenter of models (Fig. 3.4.A1), we could get the same conclusion as we got from the above cases. In the case A, without the strength of BIM, The slip amount along the front of the indenter is larger than the width of the indenter. In the case B, when the strength of BIM is 0.5 times that of the model inside, the slip amount along the front of the indenter is about half of the width of the indent. The case C has no slip between the model and the front of the indenter, when the strength between the model and indenter is as strong as the model inside. Thus, there is another test to verify that slip between the model and indenter is decided by the strength of their contact.

Fig. 3.4.A1. With another parameter setting and more indentation amount, the same effect of the BIM strength on the slip amount in front of the indenter is that the slip amount decreases as the strength of the BIM increases. Case A has no strength between the model and indenter; the strength between the model and indenter is half of the model inside in case B; Case C has the same strength between the model and indenter to the model inside.

3.5 Modeling results and comparison to the observations

With the tests we conducted in the previous sections, we make the model to simulate the large scale faulting and lithospheric-scale thickening in the India-Asia collision zone, and compare the modeling results to the nature.

3.5.1 Modeling Results

In the DEM model, a length of 1 m represents 500 km in nature. A time interval of 1 s represents about 0.124 million years. The width of the indenter is 5 m, equivalent to the 2500 km length of the Himalayan range. The thickness of the model is 0.25 m, corresponding to a 125 km-thick lithosphere. We hypothesize the India plate collided with the Asian plate 54 Million years ago. We apply a constant indentation velocity of 0.01 m/s on the model. It is scaled to represent 40.27 km/Myr (~ 4 cm/yr) in the nature. We divide the whole indentation process into 11 stages based on different geological features (e.g. the strike-slip faulting or thrusting).

We describe the 3D deformation at each stage based on the kinematic deformation, semi-transparent (the opacity of the model is 0.3, in order to show the position of thrusting.), kinematic deformation, micro crack distribution, and displacement distribution along the east-west, north-south, and vertical directions (Fig. 3.5.1 to 3.5.11). The kinematic deformation figures show the horizontal deformation in map view, and the horizontal east-west colored stripes allow to show the displacement along strike-slip faults. In order to identify the location of the thrust faults, we plot the deformation figures. In the semi-transparent kinematic model, the model is vertically divided into three layers

colored in red, green and cyan from top to bottom before the deformation and the opacity of the whole model is 0.3. With the semi-transparent kinematic deformation, when the thrust fault forms, the thrust fault will be identified based on the deep red marks (e.g. Fig. 3.5.5aII, the thrust fault will make more semi-transparent red elements overlapped together, so the thrust fault will be shown in red line.). The micro crack distribution figures show the fault location and the pattern. The figures of the displacement distribution along the east-west, north-south illustrates the offset along the strike-slip fault in the stage. The vertical distribution depicts the zone if it is deformed vertically in the stage. From deformation patterns, we can identify thrust faults, strike-slip faults and measure offset along the faults. Faults are displayed on Figs 3.5.1b- 11b. All active faults are in red, and inactive faults are in cyan in that stage. The slip rates along the faults are listed in Tables 3.5.1-9. The vertical cross-sections show the vertical shape of the faults, which is important for constructing the fault. Fig. 3.5.12 shows the position of the cross-sections. The middle one (red) located in the middle of the indenter allows to visualize the general progress of the plateau formation in Fig. 3.5.13. The generation progress of the plateau depicts that the plateau is formed step-by-step by thrusting from south to north. The combination view of horizontal and vertical deformation shows in Fig. 3.5.14. Such combination view can illustrate when the vertical deformation dominates and when the horizontal deformation is dominant. We discuss on the different features stage by stage in the following.

Stage 1

At stage 1 (Fig. 3.5.1), 2 Myrs after the onset of collision, from 54 to 52 Ma, the indenter has penetrated the model about 15.7cm (78.5 km). In this stage, the model is deformed with a right-lateral strike-slip fault on the eastern tip of the indenter and a mountain range in front of the indenter. The right-lateral strike-slip fault, named D1, stems from the right corner of the indenter and propagates toward the northwest. Besides small elastic deformation, we can measure the offset along D1 from the displacement distribution along the east-west, and north-south direction (Fig. 3.5.1a-IV,V). The slip rate of this right-lateral strike-slip fault is about 14 km/Myr (1.4 cm/yr) (Table 3.5.1). The slip amount along the strike-slip fault is 5.64 cm (28.2 km). At the same time, the mountain range rises in front of the indenter, bounded to the north by the first thrust fault T1, that nucleated at the western tip of the indenter. By comparing the indentation rate and the slip rate along T1, we deduce that ~40% of the shortening is absorbed by the strike-slip faulting in this early stage of indentation. The cross-sections (Fig. 3.5.13 A and 14 A) support that the model starts to deform vertically when the T1 nucleates.

Table 3.5.1. Slip rate, displacement of the indenter and the strike-slip faults in the scaled and original models in stage 1

Type	Slip rate (km/Ma)	Displacement (km)	Displacement in the original model (cm)
Indenter	40.27	78.50	15.70
Fault D1	14.11	28.21	5.64

Stage 2

At 50 Ma, the deformation of the model including the kinematic model (Fig. 3.5.2aI), semi-transparent kinematic model (Fig. 3.5.2aII), and fault patterns (Fig. 3.5.2b) are shown in Fig. 3.5.2. The total indentation amount is 31.8 cm (159 km).

From 52 to 50 Ma, the indenter has penetrated into the model by 16.1 cm (80.5 km). The micro crack distribution (Fig. 3.5.2aIII) and displacement distributions of the model (Fig. 3.5.2aIV, V and VI) are identified from 52 to 50 Ma. The following stages are similar.

In stage 2, as T1 propagates towards the eastern tip of the indenter, the long mountain range forms just in front of the indenter. Because there is no obvious offset along D1 during this stage, we now mark this inactive fault in cyan (Fig. 3.5.2b). As T1 develops, the mountain range in front of the indenter forms with a deep root (Fig. 3.5.13B and 3.5.14B).

Stage 3

At stage 3, the total amount of the penetration by the indenter is 64.1 cm (320.5 km) at 46 Ma. From 50 to 46 Ma (Fig. 3.5.3), the amount of penetration is about 32.5 cm (161.5 km). The second thrust fault T2 forms and then the first plateau P1 is uplifted between T1 and T2 in front of the indenter. The T1 and indenter work together to uplift and narrow the mountain range. From the micro-crack distribution (Fig. 3.5.3a-III), the first left-lateral strike-slip fault S1 may start from the left corner of the indenter.

The cross-sections (Fig. 3.5.13C and 14C) show that two thrust faults T1 and T2 both dip to the south and extend to the bottom of the whole modelled lithosphere. The T1 and T2 bound the sub-plateau P1.

Stage 4

At 44 Ma, the total amount of the penetration is 80.2 cm (401 km). From 46 to 44 Ma (Fig. 3.5.4), the indenter penetrates about 16.1 cm (80.5 km). In stage 4, the left-lateral strike-slip fault S1 and right-lateral strike-slip fault D1.1 generate conjugately roughly 45° with the indenter in front of plateau P1. The D1 re-activated and propagated further toward the northwest. The S1 starts from the left corner of the indenter. From the micro crack distribution, all the cracks occur along faults D1.1 and S1, but no uplift deformation from the transparent kinematic model. D1.1 slips at ~ 5.6 km/Myr (Table 3.5.2). The slip amount of D1.1 in this stage is 11 km, which is 2.2 cm in the original model. The slip rate of S1 is about 4.4 km/Myr (0.44 cm/yr). The slip amount of S1 is 1.8 cm (8.9 km). When S1 begins to slip, the bottom-right corner of the model starts to rotate 1.2 degrees clockwise to the east (Table 3.5.10). At the same time, the plateau P1 is narrowed. The position and the length of the T1 have very few changes.

Compared to the area of the sub-plateau P1 in the previous stage, we observe that the cross-section indicates the P1 apparently narrowed as the T1 develops in this stage (Fig. 3.5.13D and 14D).

Table 3.5.2. Slip rate, displacement of the indenter and the strike-slip faults in the scaled and original models in stage 4

Type	Slip rate (km/Ma)	Displacement (km)	Displacement in the original model (cm)
Indenter	40.27	80.50	16.10
Fault S1	4.44	8.88	1.78
Fault D1	5.55	11.10	2.22

Stage 5

During stage 5 (from 44 to 40 Ma), the indenter has moved northwards by 32.3cm (1641.5 km), reaching a cumulative displacement since onset of collision of 112.5cm (562.5 km). The main deformation during this stage is that the P2 is bounded by the third thrust fault T3 in the north and by the T2 in the south, and the T3 generates just next to the S1 in the northwest and along the D1.1 in the northeast. When the strike-slip fault starts to develop from west to east, the west segment of this fault is possible accompanied with the thrust component. On the other hand, the second left-lateral strike-slip fault S2 and its conjugate right-lateral strike-slip fault D2 nucleate. The slip on the remaining part of S1 and D2 are too small to measure on this scale. The slip rates along the S2 decrease gradually from 0.84 km/Myr at the left corner of the indenter to 0.56 km/Myr in the northeast (Table 3.5.3). Because left-lateral slip motion dominates, these two left-lateral strike-slip faults (S1 and S2) with the right-lateral strike-slip fault D0, potentially extrude the southeast part of the model toward the east. The slip rates along D0 are continuously from 3.35 km/Myr in the west to 1.12 km/Myr in the east. With slip along S1 and S2, the southeast corner of the model rotates 1.5 degrees to the southeast (Table 3.5.10). The T1, T2 (in light blue) and P1 do not have an obvious change.

The thrust fault T3 and the sub-plateau P2 are illustrated in Fig. 3.5.13E and Fig. 3.5.14E. The T3 also dips to the south.

Table 3.5.3. Slip rate, displacement of the indenter and the strike-slip faults in the scaled and original models in stage 5

Type	Slip rate (km/Ma)	Displacement (km)	Displacement in the original model (cm)
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Indenter	40.27	161.50	32.30
Fault S2	0.84	3.35	0.67
Fault S2	0.56	2.23	0.45
Fault D0	3.35	13.38	2.68
Fault D0	1.12	4.46	0.89

Stage 6

At 33Ma, the total indentation amount is approximately 168.9 cm (844.5 km). Stage 6 goes from 40 to 33 Ma (Fig. 3.5.6). In this stage, the indenter indents the model around 56.4 cm (282 km). This stage focuses on the deformation of S2, D2 and then mainly on the propagation along the S1. The profiles of S2 and D2 are very clear from the micro crack distribution. But, since the free boundary strongly affects, the S2 and D2 do not have large slip amounts. The slip rate on the S2 decreases from 2.78 to 1.1 km/Myr (Table 3.5.4) developing from the west corner of the indenter, and it becomes 1.56 at the end of the S2 affected by the propagation of the D2. The slip rate on the D2 decreases from 0.89 to 0.44 km/Myr evolving from the east corner of the indenter. On the other hand, the indentation tends to be absorbed by the slipping behavior of the large left-lateral strike-slip fault S1, which propagates from the left corner of the indenter to the east edge of the model. The slip rate of the S1 is 14.78 km/Myr (1.5 cm/yr). Due to the effects of the free boundary and the D2, the slip rate along the S1 does not change in this stage. When the S1 propagates to the east edge, it works together with the D0 to isolate the sub-block B1 towards the east. From west to east, the slip rate on the D0 increases from 1.78 to 4.45 km/Myr which is in contrast to the previous stage. As the S1 slips, the rotation of the B1 increases to 4.2 degrees (Table 3.5.10). Besides the nucleation and development of these strike-slip faults

in this stage, we also observe the continual narrowing and development of the P2. The change of T1, T2 and P1 seem negligible.

The cross-sections (Fig. 3.5.13F and 14F) demonstrate that the plateau P2 narrows when the T2 evolves more obviously. Fig. 3.5.14F shows that the strike-slip fault S1 has propagated to the east and separated the sub-block B1 from the main model.

Table 3.5.4. Slip rate, displacement of the indenter and the strike-slip faults in the scaled and original models in stage 6

Type	Slip rate (km/Ma)	Displacement (km)	Displacement in the original model (cm)
Indenter	40.27	282.00	56.40
Fault S2	2.78	19.45	3.89
Fault S2	1.11	7.78	1.56
Fault S2	1.56	10.89	2.18
Fault D2	0.44	3.11	0.62
Fault D2	0.89	6.22	1.24
Fault S1	14.78	103.47	20.69
Fault D0	1.78	12.45	2.49
Fault D0	4.45	31.12	6.22

Stage 7

At 31 Ma, the total indentation amount is about 185 cm (925 km). In stage 7 (Fig. 3.5.7), which is from 33 to 31 Ma, the indenter penetrates the scaled model around 16.1 cm (80.5 km). This stage mainly starts to open a zone at the east end of the S1. The slip rates on the S1 are 35.52, 51.62, 65.27 and 72.37 km/Myr (3.6, 5.2, 6.5, and 7.2 cm/yr) (Table 3.5.5), which increase from west to east. Compared to the north-south displacements, the west-east components are larger based on

the displacement distributions, so the sub-block B1 extrudes faster towards the east. At the end of the fault, the S1 starts to open a zone and it also continues working together with the D0 to extrude the B1. From west to east, the slip rate along the D0 increases from 16.1 to 28.75 km/Myr (from 1.6 to 2.9 cm/yr), and then decrease to 27.75 km/Myr (2.7 cm/yr). The average slip rates along the S1 and D0 are apparently different, which accounts for the B1 rotation toward the south. Furthermore, three relatively short thrust faults seems to form, which are perpendicular to the S1 at the east of the plateau. These three thrust faults are almost parallel each other and triggered by the S1 propagation. They may be related to the push-up behavior when the S1 slips. A mountain range forms in the north, next to the west part of the S1. The clockwise rotation of B1 continues, to about 5 degrees (Table 3.5.10). Along the S2 and part of D2 located at the north of the S1, there is no apparent deformation. Likewise, there seems to be no change along the T1, T2, and T3, P1 and in the P1 and P2.

The cross-sections also illustrate that the area of plateau is not changed generally (Fig. 3.5.13G and 14G). But, Fig. 3.5.14G shows the apparent open zone which is related to the large slip along the S1.

Table 3.5.5. Slip rate, displacement of the indenter and the strike-slip faults in the scaled and original models in stage 7

Type	Slip rate (km/Ma)	Displacement (km)	Displacement in the original model (cm)
Indenter	40.27	80.50	16.10
Fault S1	35.52	71.04	14.21
Fault S1	51.62	103.23	20.65
Fault S1	65.27	130.54	26.11

Fault S1	72.37	144.74	28.95
Fault D0	16.10	32.19	6.44
Fault D0	28.75	57.50	11.50
Fault D0	27.75	55.50	11.10

Stage 8

At 23 Ma, the total indentation amount is about 249.5 cm (1247.5 km). From 31 to 23 Ma (Fig. 3.5.8), the indenter penetrates the scaled model around 64.5 cm (322.5 km). The main feature in this stage is to form the third sub-plateau P3 with the continually slip along the left-lateral strike-slip fault S1. The slip rates along the S1 on the side of the B1 are 55.63, 57.85 and 61.19 km/Myr (5.6, 5.8 and 6.1 cm/yr) (Table 3.5.6), which increase from the west to the east. The T1, T2 and T3 extend to the east along the indenter. With these thrust faults extending, the sub-plateau P1 and P2 also extend. The fourth thrust faults T4 forms and the sub-plateau P3 generates. Besides the extrusion of the B1, the P2 develops, narrows and extrudes. A small sub-plateau (in pink) forms north of the S1 and west of the T2, grows to join the previous P2 to form the whole P2. The north edge (T3) of the P2 deforms one step at the junction zone with the S1. This is caused by the evolution of the S1. In addition, a new branch of the S1 named S1.1 appears from the middle of the indenter to the joining point of the S1 and D2. The S1.1 is also left-lateral moving and connecting to the S1. Why did this branch generate? The fast rotation of the B1 may account for the formation of this branch S1.1. Alternatively the extrusion of the B1 may have possibly triggered the S1.1. Because of this branch, the slip rate distribution along the D0 is divided into two parts by the S1.1. The slip rate of the D0 is maintained at 12.91 km/Myr (1.3 cm/yr) on the left side of the S1.1, and varies from 16.13 (1.6 cm/yr) to 24.81 (2.5 cm/yr) and to 16.13 km/Myr (1.6 cm/yr) again on the right side of the S1.1. The

rotation of the B1 continues and to about 7.5 degrees clockwise (Table 3.5.10). The S2 and D2 have no slip.

The thrust fault T4 starts to generate, dipping to the south. This is very clearly observed in the cross-section of Fig. 3.5.13H and 14H. The plateau P3, bounded by T4 also potentially starts to form. As the S1 propagates, the open zone which is located at the end of the S1 becomes bigger than that in the last stage (Fig. 3.5.14H).

Table 3.5.6. Slip rate, displacement of the indenter and the strike-slip faults in the scaled and original models in stage 8

Type	Slip rate (km/Ma)	Displacement (km)	Displacement in the original model (cm)
Indenter	40.27	322.50	64.50
Fault S1	55.63	445.00	89.00
Fault S1	57.85	462.80	92.56
Fault S1	61.19	489.50	97.90
Fault D0	12.91	103.24	20.65
Fault D0	16.13	129.05	25.81
Fault D0	24.81	198.47	39.69

Stage 9

At 14 Ma, the total indentation amount is about 322 cm (1610 km). Stage 9 shows the deformation from 23 to 14 Ma (Fig. 3.5.9). The indenter penetrates around 72.5 cm (362.5 km). The main feature of this stage is to form the thrust fault T5 and the fourth sub-plateau P4 which is related to the generation of the T5 and the propagation of the T4. The previous three plateaus narrow and extend to the southeast. From the point where the B1 separates from the main model, the slip rate along the S1 inside of the B1 is 41.33 (4.1 cm/yr) and 42.67 km/Myr (4.3

cm/yr) (Table 3.5.7) the northeast. The right-lateral strike-slip fault D3 forms with a slip rate of ~ 0.67 km/Myr. No motion is observed along the S2, D2 and S1 on the side of the main model. The slip rate along the D0 varies from 10.89 (1.1 cm/yr) to 15.22 km/Myr (1.5 cm/yr) from west to east. The slip along the S1 and D0 help extrude the B1 and rotate it ~ 10 degrees clockwise (Table 3.5.10). With the D0 slip and the B1 extrusion, the S1.1 moves to the east along the indenter.

The cross-sections indicate that the sub-plateau P4 starts to form as the T5 begins to develop, dipping to the south in this stage (Fig. 3.5.13I and 14I). The combination of horizontal and vertical deformation (the cross-section in Fig. 3.5.14I) shows that the open zone at the end of the S1 is even bigger than that in last stage as the S1 continues to evolve.

Table 3.5.7. Slip rate, displacement of the indenter and the strike-slip faults in the scaled and original models in stage 9

Type	Slip rate (km/Ma)	Displacement (km)	Displacement in the original model (cm)
Indenter	40.27	362.50	72.50
Fault D3	0.67	6.00	1.20
Fault S1	41.33	372.00	74.40
Fault S1	42.67	384.00	76.80
Fault D0	10.89	98.00	19.60
Fault D0	15.22	137.00	27.40

Stage 10

At 6 Ma, the total indentation amount is about 386.5 cm (1932.5 km). From 14 to 6 Ma (Fig. 3.5.10), stage 10 shows that the indenter penetrates about 64.5 cm (322.5 km). The main deformation of this stage is the thrust fault T6 and the

fifth sub-plateau P5. Coevally, the previous sub-plateau P2, P3, and P4 narrow and extend to the east. The P1 remains unchanged. The slip rate along the S1 on the side of the B1 changes slightly from 24.92 to 26.14 km/Myr (or from 2.5 to 2.6 cm/yr) (Table 3.5.8). The part of S1 which is the segment between the plateau and the open zone, slips at a rate of approximately 21.1 km/Myr (2.1 cm/yr). The clockwise rotation of the B1 increases to about 13.9 degrees. From west to east of the indenter, the D0 slip rate varies from 8.57 to 9.57 km/Myr. The third left-lateral strike-slip fault S3 starts to form. At this beginning of the S3, two or three stepped thrust faults form. The right-lateral strike-slip fault D2 slips at the rate of about 0.33 km/Myr. The S2 and the S1 on the north edge of the open zone do not deform or propagate. The S1.1 continues moving to the east along the indenter.

The cross-sections (Fig. 3.5.13J and 14J) show that the T6 begins to form with dipping to the south, forming the boundary of the P5 which lies north of the P4. The area of the plateau is clearly illustrated in cross-section of Fig 3.5.13. In Fig. 3.5.14J, the size of the open zone increases slower than the previous stages, while the S1 continues to slip.

Table 3.5.8. Slip rate, displacement of the indenter and the strike-slip faults in the scaled and original models in stage 10

Type	Slip rate (km/Ma)	Displacement (km)	Displacement in the original model (cm)
Indenter	40.27	322.50	64.50
Fault D2	0.33	2.67	0.53
Fault S1	21.14	169.10	33.82
Fault S1	24.92	199.36	39.87
Fault S1	26.14	209.15	41.83
Fault D0	8.57	68.53	13.71

Fault D0	9.57	76.54	15.31
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Stage 11

At the present, the total indentation amount is about 434.9 cm (2174.5 km). In the last stage, which is from 6 Ma to the present (Fig. 3.5.11), the indenter penetrates about 48.4 cm (242 km) in the model. The main geological feature in stage 11 is to propagate the large left-lateral strike-slip fault S2 to the east edge, and to change the sense of the S1 from the left-lateral to the right-lateral. With this right-lateral slip along the S1 at the south of the open zone, the slip may generate one more thrust fault perpendicular to the S1 next to the previous parallel three thrust faults. The slip rate along the S2 varies from 31.17 to 34.51 km/Myr (from 3.1 to 3.5 cm/yr) from west to east (Table 3.5.9). The right-lateral slip rate along the S1 at the open zone is about 12.69 km/Myr and at the B1-B2 joint zone is 7.24 km/Myr. With the formation of the S2, the conjugate fault D2 reactivates and slips 0.67 km/Myr right-laterally. The slip rate along the D0 decreases from 8.57 in the west to 7.35 km/Myr in the east. The sub-plateau P5 thickens and narrows. The clockwise rotation of the B1 increases to 15.2 degrees (Table 3.5.10), and this rotation continue to extrude the B1 to the east. This extrusion and rotation of the B1 may have had an effect on the plateau P1 and P2 which continue to extend toward the southeast. The S3 and D2 seem not to deform.

From the cross-sections (Fig. 3.5.13K and 14K), the T5 continues to develop and the P5 narrows in this stage. The S2 propagates to the edge in this stage with the T5 developing (Fig. 3.5.14K).

Table 3.5.9. Slip rate, displacement of the indenter and the strike-slip faults in the scaled and original models in stage 11

Type	Slip rate (km/Ma)	Displacement (km)	Displacement in the original model (cm)
Indenter	40.27	242.00	48.40
Fault S2	31.17	187.04	37.41
Fault S2	34.51	207.08	41.42
Fault D4	0.67	4.01	0.80
Fault S1	7.24	43.42	8.68
Fault S1	12.69	76.15	15.23
Fault D0	8.57	51.44	10.29
Fault D0	7.35	44.09	8.82

Table 3.5.10. Rotation of the sub-block B1 and Time

Time(Ma)	54	44	40	33	31	23	14	6	0
Rotation(°)	0	1.2	1.5	4.2	5	7.5	10	13.9	15.2

3.5.2 Comparison between the modeling results and nature

We compare the deformation predicted by the numerical model to Cenozoic strike-slip faulting and plateau generation in Asia (Fig. 3.5.15).

1. Around the Qinghai-Tibet plateau

Red River fault (S1)

The first strike-slip S1 fault in the model is comparable to the Red River fault. In the model, the S1 fault nucleated about 46 Ma, with a cumulative left-lateral offset of ~1200 km, and then change to dextral slip amount ~40 km from 6 Ma. The recent right-lateral slip rate along the S1 is ~7 cm/year, which is comparable to observations (5 cm/year (Tapponnier et al., 1990; Leloup et al.,

2001; Replumaz et al., 2001; Replumaz and Tapponnier, 2003)). These features make S1 fault comparable to the Red River fault.

Altyn Tagh fault (S2)

The second strike-slip fault S2 nucleates at ~40 Ma but stops slipping shortly thereafter. At 6 Ma and after the first strike-slip fault S1 has led to the extrusion and rotation of the first sub-block B1, S2 is reactivated and its cumulative slip reaches a total of 180 km. The average slip rate of S2 over the last 6 Myr is about 3 cm/year. The reactivation of S2 6 Myr ago coincides with the change in kinematics of S1, from left-lateral to right-lateral. These features, along with the S1 slip sense change, are in good agreement with the Altyn Tagh fault behavior.

Tien Shan, Altai and Baykal zone (S3)

The third strike-slip fault S3 occurs ~10 Ma before the S2 fast propagation period. The position, the mechanism behavior and its deformation time might correspond to the Tien Shan, Altai and Baykal zone.

NE-SW trend faults on Shan-Thai plateau (three parallel faults)

We can observe three adjacent parallel faults in the first sub-block B1. These three parallel faults generated about 32 Ma in my scaled model, and then rotated together with the sub-block B1. The position and morphology are general coherent with the Wanding or Nantinghe, Menlian or Mengxing, and Mae Chan faults.

Tertiary movements of Southeast Asian blocks (B1 extrusion and rotation)

The sub-block B1 started to isolate from the main block since ~40 Ma in the scaled model. The extrusion and rotation of this block B1 opened a zone at the top-right end from ~33 Ma to ~ 6 Ma. From 14 Ma to 6 Ma, the open rate of this zone is relatively very low. The sub-block B1 and open zone are in accordance with the Sundaland block and the South China Sea respectively. The sub-block B2, which is bounded by the S1 to the south and S2 to the north, was separated about 6 Ma. The position and mechanism of B2 are in generally keeping with the South-China block.

Andaman Sea (the open zone just west of the indenter)

The open zone is located between the right edge of the indenter and the sub-block B1. The scaled model shows that this open zone is formed from 32 Ma to 6 Ma. The position, shape and size of this open zone are general consistent with the opening of the Andaman Sea (Peltzer and Tapponnier, 1988).

Shanxi graben (the junction area of S2 and D2)

The location and mechanism of the junction area of the second sinistral strike-slip fault S2 and second dextral strike-slip fault D2 should be comparable to the Shanxi graben zone. Unfortunately, the scaled model does not have an open zone which could be comparable to the Shanxi graben. The open zone may be decided by other more detailed information, such as the heterogeneous strength of the lithospheric block or complicated boundary condition.

2. In the Qinghai-Tibet plateau

Karakorum fault and Zangbo fault (T1)

In our scaled model, we set the indenter to represent the Indian plate and Himalayan range together to deform the Asian plate. The first thrust fault T1 formed at the beginning of the indentation and it is just next to the indenter. The behavior of T1 is comparable to the Karakorum fault and Zangbo fault.

Bangong nujiang suture (T2)

The second thrust fault T2 in the scaled model formed about 48 Ma. The feature of T2 is comparable to the Bongong Nujiang suture. The first sub-plateau P1, bounded by T1 and T2 , corresponds to the southern half of the Eocene Tibet (Fig. 3.1.3 in section 3.1) of Tapponnier et al (2001) and not agree with the continually thickening assumption of the soft Tibetan model (England and Houseman, 1986; Houseman and England, 1986; Royden et al., 1997; Searle and Szulc, 2005).

Tanggula shan fault (T3)

Later in the collision history, the third thrust fault T3 generated and developed around 40 Ma. and mainly narrow the P2 from 31 to 23 Ma when the sub-block B1 mainly extruding. The T3 is consistent with the Tanggula shan fault, and the P2 is equivalent to the northern half of the Eocene Tibet.

Fenghuo shan, Jinsha suture and Xianshuihe fault (T4)

After the first strike-slip fault S1 starting to extrude the sub-block B1, the fourth thrust fault T4 formed as the indenter moving more towards the north around 27 Ma. The T4 worked together with the T3 to uplift the sub-plateau P3 next to the P2. The T4 is analogous with the Fenhuo shan, Jinsha suture and

Xianshuihe fault towards the southeast and the P3 is comparable to the Qiang Tang block.

Qiman-Kunlun shan and Kunlun fault (T5)

The fifth thrust fault T5 generated next to the T4 to the north about 18 Ma in the scaled model. The T5 raised one more sub-plateau P4 between the T4 and T5. The deformation of T5 is in agreement with the Qiman-Kunlun shan and Kunlun fault. The P4 corresponds to the Oligo-Miocene Tibet.

Qilan shan and Haiyuan fault (T6)

We observe that the sixth thrust fault T6 developed north of T5 at ~ 10 Ma in the scaled model. Similar to the sub-plateau P1, P2, P3 and P4, the sub-plateau P5 was generated by the T6 development. The T5 is coherent with the Qilan shan and Haiyuan fault. The P5 is consistent with Plio-Quaternary Tibet.

Jiali fault and Nianqing Tanggula shan (S1.1)

One interesting fault we observe from the scaled model is S1.1. It started around 27 Ma when the first sub-block B1 rotated, and being active until 6 Ma when the first strike-slip fault (corresponds to the Red River fault) changed the sense from left-lateral to right lateral. The location of this fault is in accordance with the Jiali fault and Nianqing Tanggula Shan. The time of this fault is still debated, varies from 40 to 8 Ma. Thus, the location and time of the S1.1 are general consistent with the Jiali fault and Nianqing Tanggula Shan.

3.5.3 Discussion

We first demonstrate that the rotation amount of the sub-block B1 varies with time (Fig. 3.5.16 and Table 3.5.10). From the curve, we observe the slope of the curve from 40 to 6 Ma is steeper. From 40 to 6 Ma, this is the period that the S1 was simply moving. Thus, the sub-block B1 rotates faster when the S1 evolves. Relatively, before 40 Ma, and after 6 Ma, the rotation amount of the B1 increases more slowly. When mainly thickening, B1 still rotates clockwise but at a slower rate. Coherently, the B1 block (comparable to the Sundaland block) rotated rapidly when the S1 (comparable to the Red River) propagated and the B1 block still had slow rotation before the S1 formed and after the S1 changed the sense. In addition, we identify the pole of the sub-block B1 rotation by overlapping the profiles of the deformed model together in Fig. 3.5.17. The pole is located in the south of B1.

We also interpret the final thickened amount of the lithosphere in Fig. 3.5.18. The maximum of the deformed lithosphere under the plateau is 390 km, which is about three times the initial undeformed lithosphere thickness (125km). The average thickness of the deformed modeled lithosphere under the plateau is 236 km, which is 1.8 times that of the initial lithosphere. The initial thickness of the modeled continental lithosphere is about 125 km, and that under the modeled plateau is around 250 km. The average thickness of the deformed lithosphere in the scaled model (236 km) is comparable with the observation (Wittlinger et al., 2004). Furthermore, as we mentioned in the above description, the plateau is formed progressively from south to north away from the indenter. Why it is formed following such pattern not continuously? The strength of the lithosphere

determines the thickened thickness. When the thickness of the deformed lithosphere reaches the limit, it cannot be deformed any more, and it has to choose to deform next zone by faulting. This zone is close to the previous deformed zone. This is the reason why the plateau is formed with several sub-plateaus (deformed zones) by several thrust faulting step-by-step progressively from south to north.

Finally, we calculate the volume of the lithosphere thickening and shortened volume by the indenter. The volume of the lithosphere thickening is the total volume of spherical elements which are above the surface of the initial lithosphere or below the bottom of the initial lithosphere. The shortened volume by the indenter is the sum of volume of spherical elements which located in the indented space. We did not consider the porosity change from the initial model to the thickened model. However, when calculating the spheres above or below the initial model, we computed the sum of the volume of spheres if the center of spheres is above or below the initial model to be the `min_errorBar`; and computed the volume of the sphere if the center of spheres is above or below the initial model to be the `max_errorBar`. Generally, the real thickened volume of the lithosphere should be close to the average curve (red curve in Fig. 3.5.19). The ratio of total thickened volume of the lithosphere to total shortened volume by the indenter (Fig. 3.5.19) illustrates the relationship between the horizontal and vertical deformation. At the beginning, the shortening of the indenter is mainly absorbed by the lithospheric-scale thickening as shown by a very fast increase of the ratio before 46 Ma. The first plateau P1 was formed at that time and it is in accordance with the south part (Eocene Tibet south of Bangong-nujiang suture) of

the Qinghai-Tibet plateau. From 46 to 44 Ma, there is a small drop on the curve. This drop may correspond to the initiation of S1 and D1.1 strike-slip faults. Thus, the accommodation of shortening by the indenter partially shifts to strike-slip faulting. After this drop, there are two more big drops on the curve: one is from ~35 to 23 Ma and another one is from 6 Ma to the present. During these two periods, S1 and S2, analogous to Red River and Altyn Tagh faults respectively, developed in the scaled model. Besides, the curve contains two flat parts from 44 to 35 Ma and from 23 to 6 Ma. During these two periods, deformation in the scaled model was dominated by thickening. From 44 to 35 Ma, the sub-plateau P2 formed (it corresponds to the part between the Tanggula Shan and Bangong-nujiang suture). From 23 to 6 Ma, the sub-plateaus P4 and P5 formed, analogous to the Oligo-Miocene Tibet (between the Jinsha suture and the Kunlun fault) and the Plio-Quaternary Tibet (between the Kunlun fault and Qilian Shan) respectively. The sub-plateau P3, which corresponds to the region between Tanggula Shan and Fenghuo Shan, deformed together with the strike-slip faulting. This deformation is not indicated in the ratio curve of the thickening to shortening. In the following section, we will discuss the alternation between horizontal and vertical deformations more quantitatively.

Fig. 3.5.1a. The deformation, micro crack distribution, and the displacement field of the model from 54 to 52 Ma, when the total indentation is about 78.5 km in the scaled model and 15.7 cm in the original model. In the above figures, the unit of displacement is cm.

Fig. 3.5.1b. Fault patterns, scaled indentation and fault slip rates from 54 to 52 Ma: the shortening indentation rate is 40.27 km/Ma; the slip rate along the right-lateral fault D1 is 14.1 km/Ma; the first thrust fault T1 starts to form.

Fig. 3.5.2a. The deformation, micro crack distribution, and the

displacement field of the model from 52 to 50 Ma, when the total indentation is about 159 km in the scaled model and 31.8 cm in the original model. In the above figures, the unit of displacement is cm.

Fig. 3.5.2b. Fault patterns, the scaled indentation rate from 52 to 50 Ma: the right-lateral fault D1 is not active during this period, but the thrust fault T1 develops.

Fig. 3.5.3a. The deformation, micro crack distribution, and the

displacement field of the model from 50 to 46 Ma, when the total indentation is about 320.5 km in the scaled model and 64.1 cm in the original model. In the above figures, the unit of displacement is cm.

Fig. 3.5.3b. Fault patterns, plateau area and scaled indentation rate from 50 to 46 Ma: the second thrust fault T2 forms and develops a sub-plateau P1 with the T1 faulting; the first left-lateral strike slip fault S1 may start to generate from the left corner of the indenter.

Fig. 3.5.4a. The deformation, micro crack distribution, and the

displacement field of the model from 46 to 44 Ma, when the total indentation is about 401 km in the scaled model and 80.2 cm in the original model. In the above figures, the unit of displacement is cm.

Fig. 3.5.4b. Fault patterns, plateau area, scaled indentation and fault slip rates from 46 to 44 Ma: the slip rate along the S1 is 4.4 km/Ma; the slip rate along the right-lateral fault D1.1 is 5.6 km/Ma; the plateau area is same as the last period.

Fig. 3.5.5a. The deformation, micro crack distribution, and the displacement field of the model from 44 to 40 Ma, when the total indentation is about 562.5 km in the scaled model and 112.5 cm in the original model. In the above figures, the unit of displacement is cm.

Fig. 3.5.5b. Fault patterns, plateau area, scaled indentation and fault slip rates from 44 to 40 Ma: the slip rate along the second left-lateral strike slip fault S2 is about 0.7 km/Ma; the right-lateral fault D0 slip rate varies from 3.4 to 1.1 km/Ma from the left to right corner of the indenter; the third thrust fault T3 generates and forms the second sub-plateau P2 next to P1.

Fig. 3.5.6a. The deformation, micro crack distribution, and the displacement field of the model from 40 to 33 Ma, when the total indentation is about 844.5 km in the scaled model and 168.9 cm in the original model. In the above figures, the unit of displacement is cm.

Fig. 3.5.6b. Fault patterns, plateau area, scaled indentation and fault slip rates from 40 to 33 Ma: the slip rates along the S1 and S2 are about 14.8 and 2 km/Ma respectively; the D0 slip rate changes from 1.8 to 4.5 km/Ma from the left to right corner of the indenter; the D2 slip rate is about 0.6 km/Ma; the sub-plateau P2 is narrowed in this period.

Fig. 3.5.7a. The deformation, micro crack distribution, and the displacement field of the model from 33 to 31 Ma, when the total indentation is about 925 km in the scaled model and 185 cm in the original model. In the above figures, the unit of displacement is cm.

Fig. 3.5.7b. Fault patterns, plateau area, scaled indentation and fault slip rates from 33 to 31 Ma: the slip rates along the S1 increases from 35.5 to 72.4 km/Ma from west to east; the D0 slip rate increases from 16.1 to 28.8 and then decreases a little to 27.8 km/Ma from west to east; the S2 and D2 are not active in this stage; the first sub-block B1 is isolated from the main block.

Fig. 3.5.8a. The deformation, micro crack distribution, and the displacement field of the model from 31 to 23 Ma, when the total indentation is about 1247.5 km in the scaled model and 249.5 cm in the original model. In the above figures, the unit of displacement is cm.

Fig. 3.5.8b. Fault patterns, plateau area, scaled indentation and fault slip rates from 31 to 23 Ma: the slip rates along the S1 still increases from 55.6 to 61.2 km/Ma from west to east; the D0 slip rate increases from 12.9 to 24.8 and then decreases to 16.1 km/Ma from west to east and the S1.1 forms; the fourth sub-plateau T4 forms and generates the third sub-plateau P3 next to the S1; the B1 rotates to the south-east and open a zone at the right tip of the S1.

Fig. 3.5.9a. The deformation, micro crack distribution, and the displacement field of the model from 23 to 14 Ma, when the total indentation is about 1610 km in the scaled model and 322 cm in the original model. In the above figures, the unit of displacement is cm.

Fig. 3.5.9b. Fault patterns, plateau area, scaled indentation and fault slip rates from 23 to 14 Ma: the slip rates along the S1 is about 42 km/Ma; the D0 slip rate increases from 10.9 to 15.5 km/Ma from west to east and the S1.1 propagates; the slip rate of the D3 is about 0.7 km/Ma; the fifth sub-plateau T5 forms and rises the fourth sub-plateau P4 next to the P3 northward; the P1, P2 and P3 are narrowed; the rotation of the B1 increases to the south-east and the open zone becomes bigger.

Fig. 3.5.10a. The deformation, micro crack distribution, and the displacement field of the model from 14 to 6 Ma, when the total indentation is about 1932.5 km in the scaled model and 386.5 cm in the original model. In the above figures, the unit of displacement is cm.

Fig. 3.5.10b. Fault patterns, plateau area, scaled indentation and fault slip rates from 14 to 6 Ma: the slip rates along the S1 is about 21 km/Ma at the connection zone and the S1 has about 25 km/Ma moving rate at the open zone; the D0 slip rate increases from 8.6 to 9.6 km/Ma from west to east; the slip rate of the D2 is about 0.3 km/Ma; the third left-lateral strike slip fault S3 starts next to the S2 northward; the sixth sub-plateau T6 generates and rises the fifth sub-plateau P5 next to the P4 northward; the P2, P3 and P4 are narrowed; the rotation of the B1 continues increasing to the south-east.

Fig. 3.5.11a. The deformation, micro crack distribution, and the displacement field of the model from 6 to the present, when the total indentation is about 2174.5 km in the scaled model and 434.9 cm in the original model. In the above figures, the unit of displacement is cm.

Fig. 3.5.11b. Fault patterns, plateau area, scaled indentation and fault slip rates from 6 to the present: the S1 changes from left-lateral to right-lateral and its slip rate is about 7 km/Ma at the connection zone and about 12 km/Ma moving rate at the open zone; the S2 rejuvenates and propagates with the slip rate about 33 km/Ma to the east boundary of the model and the S3 stops; the D0 slip rate decreases from 8.6 to 7.4 km/Ma from west to east; the slip rate of the D4 is about 0.7 km/Ma; the P5 is narrowed.

Fig. 3.5.12. Cross-section positions: the red and blue lines show the position of the cross section, which are 15 and 16 m from the left corner of the model respectively. The pink, cyan, and green lines show the cross sections located away from the left corner 13, 14, 17 m respectively. The pink, cyan, and green cross sections are interpreted in the Appendix)

Fig. 3.5.13. Plateau stepwise rising by thrust faults from south to north, shows in the cross section which is located 15 m from the left corner of the model.

Fig. 3.5.14. Plateau generation and strike slip faulting in the cross section 16 m from the left corner of the indenter.

Fig. 3.5.15. Comparison of the model results to the nature; The entire plateau comprises of five sub-plateaus bounded by the thrust faults. The first left-lateral strike slip fault S1 changed the sense when the second left-lateral strike slip fault S2 propagates. This feature is consistent with the Red River fault. The mechanism of S2 is comparable to the Altyn Tagh fault.

Fig. 3.5.16. Rotation of the sub-block B1 (corresponds to the Sundaland block) increases with time.

Fig. 3.5.17. Rotation pole P of the sub-block B1 is determined based on all deformation states.

Fig. 3.5.18. Cross section (16 cm from the left corner of the model, and 1750 km from the left corner of the indenter and 750 from the right corner of the indenter in the scaled model): the maximum thickened lithosphere is 390 km, which is about three times the initial lithosphere thickness (125km); the average

thickness of the deformed lithosphere at the Plateau area is 236 km, which is 1.8 times that of the initial lithosphere.

Fig. 3.5.19. The illustration of the ratio of the volume of the thickened lithosphere to the shortened volume by the indenter with time.

Appendix 3.5

More cross sections show more detail information about the vertical deformation of the model. These cross sections show the depth of the plateau increases from north to south, which is consistent to the observation (Vergne et al., 2002; Wittlinger et al., 2004; Tseng et al., 2009).

Fig. 3.5.A1. Vertical deformation in the cross section which is 13 m from the left corner.

Fig. 3.5.A2. Vertical deformation in the cross section which is 14 m from the left corner

Fig. 3.5.A3. Vertical deformation in the cross section which is 16 m from the left corner

Fig. 3.5.A4. Vertical deformation in the cross section which is 17 m from the left corner

3.6 Seismicity to profile fault nucleation and propagation

Analyzing focal mechanisms is important for determining fault type. In discrete element modeling, the fault is located along the profile of the micro-crack cluster. This is like using the cluster of seismicity to determine the fault in nature. In this section, we focus on the analysis of the micro-cracks in the scaled model.

How do we determine the focal mechanism of micro seismicity (micro-crack) in DEM model? As we mentioned in Chapter 2, the focal mechanism of the micro seismicity is based on the direction of the movement of spherical elements past each other. For example, take two bonded spherical elements (Fig. 3.6.1): the slip vector shows the moving direction of the upper sphere. The direction of the slip vector is the same as the resultant force (the resultant force is equal to shear force vector plus normal force vector). But the slip vector may be different from the shear direction. The null vector is equal to the shear force cross multiplied by the normal force (the null vector is the cross product of the shear force vector and the normal force vector). The null vector is perpendicular to the plane which contains shear force, normal force, resultant force and the slip vector. The other plane which comprises the slip vector (the resultant force) and the null vector, is the slip plane. An auxiliary vector is defined as the resultant force cross multiplied by the null vector (the auxiliary vector is the cross product of the resultant force vector and the null vector). The null vector and auxiliary vector form the plane defined as the auxiliary plane. Based on this algorithm, we identify the focal mechanisms of seismicity as shown in Fig. 3.6.1.

Using the results from the above algorithm, we plot the fault plane solutions for micro-seismic events that occurred in the upper third of the lithosphere (Fig. 3.6.2) equivalent to the seismicity in the crust. We depict the micro-seismic events for every 2 million years and analyze them referring to the fault distribution in the previous section. The thrust events are in red, strike-slip events are in green and normal events are in blue. For the normal events, we color the center of fault plane solution in blue, rather than the surrounding part in blue, in order to make the fault plane solution easier to be seen. In Fig. 3.6.3, we plot the percentage of each type of faulting as a function of time.

In Fig. 3.6.2a (From 54 to 52 Ma), the two clusters of micro seismicity events reveal two faults: thrust fault T1 and strike-slip fault D1 (in Fig. 3.5.1). Fault plane solutions for these events indicate more thrust (red) and relatively less normal (blue) and strike-slip (green) senses in the first 2 million years after the collision. It is clear from Fig. 3.6.3 that deformation is largely dominated by thickening, which is compatible with our faulting analysis for stage 1 in the previous section.

In stage 2 (from 52 to 50 Ma), the cluster of micro-seismic events (Fig. 3.6.2b) demonstrates more thrust events, which means thrust faulting is still dominant. The strike-slip sense events increase which might be caused by strike-slip component of the thrust fault (T1) (Fig. 3.5.2), which slip component along the interface of the indenter and the model.

Stage 3, the period from 50 to 46 Ma, is divided into two steps (Fig. 3.6.2c and 2d). In the first 2 million years, both T1 and T2 (Fig. 3.5.3) developed, where T2 mainly evolved in the latter 2 million years. In these 4 million years, thrust sense events are still dominant. We observe the zone surrounded by the seismic events and the indenter, which is the sub-plateau P1. In this zone, few micro-seismicity events occurred. Internal deformation is negligible in P1, but there is faulting occurring around P1.

In stage 4 (from 46 to 44 Ma), besides the slip component along T2 (more strike-slip sense events on T2) (Fig. 3.5.4), strike-slip faults S1 and D1.1 nucleate from two corners to the middle of the indenter and generate a triangle zone, which can be identified based on two clusters of strike-slip sense events (Fig. 3.6.2e).

In stage 5 (from 44 to 40 Ma), more strike-slip sense events (Fig. 3.6.2f and g) occur in the narrow fault zones inside the model, and north of thrust sense events (T2) (Fig. 3.5.5). The event clusters shows that T2 continues to develop, and the clusters in narrow lines suggest that the strike-slip faults (S1, S2, and D2) are long and slipping in narrow zones. In Fig. 3.6.3, the analysis of the numbers of the seismicity senses show that the number of thrust (red) events drop sharply related to two other senses, but the strike-slip (green) events increase rapidly.

From 40 to 33 Ma in stage 6 (Fig. 3.6.2h, i, j and k), S1, S2, D2 and T2 (Fig. 3.5.6) continue to develop. T2 is primarily composed of red focal mechanisms in front of the indenter. The strike-slip faults S1, S2 and D2 slip along narrow shear

zones, based on the concentrated clusters of seismicity. From 40 to 36 Ma, the further north part of the model is deformed by S2, D2, which happens before S1 propagates to the east edge. These three faults include more strike-slip sense events (green), few normal sense events (blue), rare thrust events (red). When strike-slip fault slips, normal micro-cracks are usually developing concurrently, and very few thrust micro events also occur. From 36 to 33 Ma, the events along S2 and D2 occurred less often, whereas events along S1 happened more often. After S1 propagated to the edge, S2 and D2 become less and less active, and finally cease movement. Thus, the main development during this state is that S1 propagated to the edge, and there was propagation of the two small two strike-slip faults (S2, and D2). The number of thrust events (red in Fig. 3.6.3) still drops sharply, whereas the number of the strike-slip (green in Fig. 3.6.3) event increases dramatically. Around 33 Ma, the number of thrust events is equal to that of strike-slip events.

In stage 7 from 33 to 31 Ma (Fig. 3.6.2k and l), strike-slip sense events occur on S1. Very few events (Fig. 3.6.2l) occurred along the D2 (Fig. 3.5.7) segment in the sub-block (B1) which means that D2 is less active after S1 propagated to the edge. More thrust sense events concentrate northward of S1, which starts to form thrust fault T4. Fig. 3.6.3 shows that thrust sense events (red) still decrease, and strike-slip sense events (green) increase. This is because this strike-slip fault mainly slips to extrude S1 and to open the zone at the east end of the fault.

From 31 to 23 Ma (in stage 8, Fig. 3.6.2l, m, n, o and p), the sub-plateau P3 (Fig. 3.5.8) formed, S1 extruded, and B1 and S1.1 propagated across the sub-plateaus P1 and P2. From the micro-seismicity distribution, the zone between T4 and S1 has few micro-seismicity events, which corresponds to the sub-plateau P3 (Fig. 3.6.1l). During the first 3 million years (Fig. 3.6.2l and m), S1 propagated with more strike-slip sense events and less thrust or normal sense events along it. From 28 Ma, S1 became shorter as B1 extruded and rotated from the main block, because the open zone at the end of S1 expanded. When the open zone enlarged, the fault S1.1 appeared from the middle of the indenter, connecting to S1, around 28 Ma. This fault became one branch of S1 across the plateau zone. The seismicity cluster along S1.1 has more strike-slip sense events and less thrust or normal sense events. The events along S1.1 become fewer from 28 Ma to 23 Ma. In this stage, the number of strike-slip events is bigger than that of thrust events (Fig. 3.6.3). This generally means more strike-slip faulting rather than thickening.

From 23 to 14 Ma (stage 9), we interpret the seismicity clusters to mean that the sub-plateau P4 (Fig. 3.5.9) was formed when the thrust fault T5 developed, and S1 continued to slip (Fig. 3.6.2p, q, s and t). Furthermore, S1.1 was less active from 23 to 18 Ma (Fig. 3.6.2p and q) and there is almost no action from 18 to 16 Ma (Fig. 3.6.2r and s), but it reactivated from 16 to 14 Ma (Fig. 3.6.2t). Since thrusting (thickening) is dominant, thrust sense events are more than strike-slip sense events (Fig. 3.6.3).

From 14 to 6 Ma (stage 10), the sub-plateau P5 (Fig. 3.5.10) formed by the thrust fault T6 developed with lots of thrust sense events. The third strike-slip

fault S3 tended to slip with several seismic events. S1 continued to rotate B1 and the S1 shortened as the open zone expands between B1 and the main model. S1.1 became more active from 14 to 12 Ma, and tended towards less and less activity from 12 to 8 Ma, and then had no slip events from 8 to 6 Ma.

From 6 Ma to the present (stage 11), the main features are that the strike-slip fault S2 (Fig. 3.5.11) reactivated and propagated to the edge, and S1 changed from left-lateral to right-lateral motion. These features are consistent with the results in the previous section. From 6 to 4 Ma, T6 developed with very few events inside of the plateau. Three strike-slip faults (D2, D4, S2) formed, which is identified from clusters of seismic events. In addition, very few events occurred along S3. From 4 to 2 Ma, lots of strike-slip sense events happened along S2 and allowed it to propagate to the edge. At the same time, we observe that D4 also slipped based on a seismic cluster. In the most recent 2 million years, few cracks occurred along D2, but more strike-slip sense events occurred along S2. Furthermore, some events occurred along the S1, since it changed the slip sense from left-lateral to right-lateral. The number of the events (Fig. 3.6.3) shows that the strike-slip sense events are more than thrust events from 4 Ma to present. The thrust events drop strongly and strike-slip increase critically from 6 Ma.

The ratio curves of thrust, normal and strike-slip senses to the total number of micro-seismicity events (Table 3.6.1 and Fig. 3.6.3) suggest thrust events decrease from 52 to 26 Ma, and generally increase from 26 to 8 Ma, and then decrease again in the most recent 8 Myrs. Conversely, strike-slip faulting generally increases from 52 to 26 Ma, going down from 26 to 8 Ma, and going up

again in the most recent 8 Myrs. Normal faults are stable, about 30% for the whole collision process. These characters are exactly consistent with the fault observation from the scaled model, and in general accordance with nature.

Table 3.6.1. Numbers of three senses of fault during each period

time	normal	thrust	strike-slip
54-52	190	497	74
52-50	194	459	151
50-48	282	579	201
48-46	239	514	190
46-44	298	608	199
44-42	338	656	268
42-40	326	537	229
40-38	377	552	317
38-36	372	499	375
36-34	400	495	419
34-32	523	530	493
32-30	364	432	463
30-28	356	407	424
28-26	353	344	407
26-24	340	397	391
24-22	369	389	371
22-20	318	389	302
20-18	329	439	348
18-16	316	469	352
16-14	320	436	330
14-12	360	495	372
12-10	344	525	380
10-8	408	581	391
8-6	391	506	359
6-4	388	494	436
4-2	708	630	771
2-0	624	506	772

Fig. 3.6.1. Illustration of focal mechanism calculation at micro scale in DEM:
A focal mechanism is comprised of the slip plane and the plane which is perpendicular to the slip plane and contains the auxiliary vector.

1-3 (*10000 steps)

(a) 54-52 Ma; stage 1

3-5 (*10000 steps)

(b) 52-50 Ma; stage 2

5-7 (*10000 steps)

(c) 50-48 Ma; stage 3 – part 1

7-9 (*10000 steps)

(d) 48-46 Ma; stage 3 – part 2

9-11 (*10000 steps)

(e) 46-44 Ma; stage 4

11-13 (*10000 steps)

(f) 44-42 Ma; stage 5 – part 1

13-15 (*10000 steps)

(g) 42-40 Ma; stage 5 – part 2

15-17 (*10000 steps)

(h) 40-38 Ma; stage 6 – part 1

17-19 (*10000 steps)

(i) 38-36 Ma; stage 6 – part 2

19-21 (*10000 steps)

(j) 36-34 Ma; stage 6 – part 3

21-23 (*10000 steps)

(k) 34-33 Ma; stage 6 – part 4 and 33-32 Ma; stage 7 – part 1

23-25 (*10000 steps)

(l) 32-31 Ma; stage 7 – part 2 and 31-30 Ma; stage 8 – part 1

25-27 (*10000 steps)

(m) 30-28 Ma; stage 8 – part 2

27-29 (*10000 steps)

(n) 28-26 Ma; stage 8 – part 3

29-31 (*10000 steps)

(o) 26-24 Ma; stage 8 – part 4

31-33 (*10000 steps)

(p) 24-23 Ma; stage 8 – part 5 and 23-22 Ma; stage 9 – part 1

33-35 (*10000 steps)

(q) 22-20 Ma; stage 9 – part 2

35-37 (*10000 steps)

(r) 20-18 Ma; stage 9 – part 3

37-39 (*10000 steps)

(s) 18-16 Ma; stage 9 – part 4

39-41 (*10000 steps)

(t) 16-14 Ma; stage 9 – part 5

41-43 (*10000 steps)

(u) 14-12 Ma; stage 10 – part 1

43-45 (*10000 steps)

(v) 12-10 Ma; stage 10 – part 2

45-47 (*10000 steps)

(w) 10-8 Ma; stage 10 – part 3

47-49 (*10000 steps)

(x) 8-6 Ma; stage 10 – part 4

49-51 (*10000 steps)

(y) 6-4 Ma; stage 11 – part 1

51-53 (*10000 steps)

(z) 4-2 Ma; stage 11 – part 2

53-55 (*10000 steps)

(aa) 2-0 Ma; stage 11 – part 3

Fig. 3.6.2. Focal mechanism distribution of micro seismicity events in the different stages: Red, thrust pattern events; Blue, normal pattern events; Green, strike slip pattern events.

Fig. 3.6.3. Ratios of thrust, normal and strike-slip senses to the total number of the seismic events, to illustrate the mainly thickening or dominant strike-slip faulting during different periods.

3.7 Comparision of the deformation velocities in the 3D simulation to the GPS velocities

The global positioning system (GPS) is an important technology to measure tectonic deformation. We take advantage of this technique to help us understand the plate deformation. Using GPS, one can determine the deformation velocities of plates (Fig. 3.7.1). To further illuminate this 3D model, we compare the velocities in the 3D model to the GPS velocities.

Fig. 3.7.1. GPS velocities in the Qinghai-Tibet zone showing the plate motion influenced by the active faults (refer to stable Eurasia (Kreemer et al., 2014))

3.7.1 Velocity arrows in the 3D model

The velocity field of the 3D model incorporates both horizontal and vertical motions of the plates. Stage by stage (Fig. 3.7.2), the horizontal velocities show their direction and values controlled by the strike-slip faults. The vertical deformation, including uplifting and root generation, occurs primarily at the edge of the plateau, with very little deformation within the plateau.

From stages 1 to 4, the entire mountain range moves to the north together with the indenter. The vertical motion of the mountain range is primarily down, as it has a larger root than its uplift. From stages 4 to 5, the zone moving to the north changes from the mountain range to the triangular zone. The vertical velocity is

only noticeable along the boundary of the triangular zone, where the second mountain range forms, with negligible vertical deformation within the triangular zone.

From stages 5 to 6, the entire sub-block B1 (Fig. 3.7.3) is isolated from the main block along the left-lateral strike-slip fault S1 and moves towards the east. The horizontal velocity changes direction from north to northeast and then to east along the S1, with the direction change caused by the S1 formation. The magnitude of the velocity of the B1 increases from the collision zone to the northeast of the S1. The opening zone starts to form at the northeast end of the S1 from stages 6 to 7 (Fig. 3.7.4). Along this opening zone, the B1 rotates towards the southeast according to the velocity gradient. Along the S1, the velocity increases in magnitude from the collision zone to the east edge in stage 7, instead of decreasing during stage 6. From the left corner of the indenter to the east edge along S1, most of the vertical deformation changes from being dominantly down-going to primarily up-going behavior. The up-going behavior at the east edge is caused by that buoyancy force prevailing during the opening zone formation.

From stages 7 to 10, the horizontal velocity and the rotation velocity of the B1 decrease. Along the S1, this velocity increase from left to right gradually recedes. The velocity of B1 decreases and its rotation becomes increasingly slower. The horizontal velocity direction of the triangular zone (plateau) changes from northeast to north again. During the plateau propagation, the vertical deformation range moves from south to north step by step, with no obvious vertical motion occurring within the plateau.

From stages 10 to 11 (Fig. 3.7.5), the second sub-block B2 extrudes to the east with the S2 propagation towards the edge of the model. The isolated sub-block B2 moves faster towards the east, relative to speed of the B1. The extrusion and rotation of the B1 continue to decrease in comparison to the previous stage. The S1 changes sense from being left-lateral to right-lateral. The direction of the triangular zone (plateau) starts to change from north to northeast again. Similar to the S1 formation, the vertical velocities along the S2 change from primarily down-going at the left corner of the indenter to predominantly up-going at the east end.

In summary, the horizontal motion of the triangular zone (plateau) propagates from north to northeast, then further north, and again to the northeast. The motion along the strike-slip fault S1 gradually varies from relatively large velocities at the collision zone to relatively lower velocities at the edge, before the S1 propagates towards the edge. After the S1 propagates to the edge, the motion along the S1 varies from relatively small at the collision zone to relatively large near the edge. This motion then reverts to its original behavior of relatively large motion at the collision zone to relatively small motion near the edge. In general, both the motion along the S1 and the rotation of the B1 decrease. Finally, the sense of the S1 changes from left-lateral to right-lateral after the second strike slip fault S2 forms. In addition, the vertical motion always occurs only along the boundary of the entire plateau, which is consistent to the hypothesis proposed by Tapponnier et. al. [Meyer *et al.*, 1998; Tapponnier *et al.*, 2001].

Fig. 3.7.2. Horizontal and vertical velocities in the model showing the deformation during these 11 stages: horizontal velocities are controlled by the strike-slip faults, whereas the vertical velocities are influenced by the thrust faults. The vertical motion occurs only along the edge of the plateau, with little motion within the plateau.

Fig. 3.7.3. Velocity field with active faults and the isolated sub-block B1 at Stage 6 of the model, showing that the direction of the velocity changes from north at the collision zone to northeast at the edge along the S1.

Fig. 3.7.4. Velocity field with active faults and the isolated sub-block B1 at Stage 7 showing that the magnitude of the velocity increases as the direction shifts from the northeast at the collision zone toward the east at the edge along the S1.

Fig. 3.7.5. Velocity field with active faults and the isolated sub-block B1 and B2 at Stage 11 showing that the direction of the velocity changes from northeast at the collision zone to east at the edge along the S1, along with left-lateral motion along the S2 and right-lateral motion along the S1.

3.7.2 Comparison of the deformation velocities in the model to the GPS velocities

The GPS velocity field (Fig. 3.7.1) shows that the Tibetan plateau is generally moving towards the north and east. We compare the GPS velocities to the deformation velocity field of the model (Fig. 3.7.5) during the most recent stage with regards to the following aspects:

1. From the GPS velocities, the velocity value decreases from ~ 5 cm/yr at the collision zone to ~ 1 cm/yr at the north edge of the plateau (Fig. 3.7.1), and the direction of velocity is strongly influenced by the active faults. In the model, the plateau zone, which is bounded by the S2, D0, and D2 (Fig. 3.5.11b), has a northward velocity of ~ 5 cm/yr. The velocity direction of the zone between the S1 and S2 changes from northward to northeastward across D2 then from northeastward to eastward across D4. The results from the GPS velocities and the simulation mode are mostly consistent.
2. The GPS velocity field shows left-lateral motion along the Altyn Tagh fault (S2) and right-lateral motion along the Red River fault (S1) which are reproduced in stage 11 of the model.
3. The GPS velocities depict relatively slow motion for the Sundaland block (Fig. 3.7.1), and fast motion for the South China block, which extrude primarily to the east. These features are also apparent at stage 11 of model (Fig. 3.7.5).

3.8 Frequency analysis of thickening and horizontal deformation

In previous sections, we observed that the horizontal deformation, such as strike-slip faulting, and vertical deformation, including plateau generation, seemed to alternate during the modeled India-Asia collision. However, how the model deformation is coeval to the alternation is not clear. How they alternate, when the vertical deformation dominates and when deformation is mainly horizontal are not well known. Whether this alternation can be related to the observed ages and duration of thrust and strike-slip deformation are extremely interesting. To understand this alternation, we have run the model and recorded 361 moments. Two successive moments are separated by 2000 time steps, which correspond to 0.15 million years. We investigate the indentation volume change (corresponds to shortening volume change; grey data in Fig. 3.8.1), the vertical deformation change (corresponds to thickening volume change; orange data in Fig. 3.8.1) for each interval moment.

To illustrate how we calculate the volume changed for each 0.15 Myrs, we will take two moments (M1 and M2) as an example. The indentation volume change in this interval is the volume of all spherical elements in the indentation zone of this period between two moments. The vertical volume change in the same interval is the volume of the spherical elements which are extruded completely from top and bottom of the scaled model at M2 subtracting that at M1 in the cross-section view (Fig. 3.8.2).

The indentation volume change is shown by the gray line and points in Fig. 3.8.1. We observe that this volume change is generally constant. This is expected

as the rate of indentation is an input parameter of our model. The indentation volume will transfer into vertical deformation (mainly thickening through thrusting) and horizontal deformation (mainly strike-slip faulting). The thickening volume change is shown by the orange line and points in Fig. 3.8.1. Since we consider that the indentation volume must be equal to the sum of the vertical and horizontal deformation, then the indentation volume change transferred to the horizontal deformation is equal to the difference between the indentation volume and the thickening volume. This volume change is shown in by the light blue line and points in Figure 3.8.1.

We will focus on the vertical deformation data, as it was obtained independently of the indentation data, to find temporal patterns of deformation. To do so, we use a Fast Fourier transform (Van Loan, 1992) to calculate the power spectrum of the thickening change curve (orange line in Fig. 3.8.1). In Fig. 3.8.3, we can see that there is an inflection at 2.56 Ma, with most of the power found at longer periods than this. Within this period band, the signal is dominated by 3 peaks at 27, 11 and 4.2 Ma (we will call P1, P2 and P3 respectively). They are marked in blue, green and purple boxes, respectively. To remove the low period noise (<2.56 Ma), we use a 2nd order, Butterworth low-pass frequency (high-pass period) filter (Butterworth, 1930) with a cut-off period of 2.56 Myrs (red box in Fig. 3.8.3). The curve after such filtering is shown as a red bold line in Fig. 3.8.1 and 3.8.4. We use the same cut-off period to filter the horizontal deformation data (light blue line with points in Fig. 3.8.1), and obtain a curve shown in dark blue. We now use band-pass filters to analyze the 3 main peaks. The bands that we use to filter the data should include the corresponding peaks and cannot be too

narrow in order to avoid large impulse errors. Thus, we choose the band from one valley to the next (e.g. blue box in Fig. 3.8.3). The sine waves to correspond to the peaks at 27, 11 and 4.2 Ma (blue, green and purple boxes, respectively, in Figure 3.8.3) are shown as blue, green and purple curves, respectively, in Figure 3.8.4.

In order to unveil the alternating relationship between vertical and horizontal deformation of the model, we compare the obtained curves to the observed deformation events in the model (Fig. 3.5.1-11 in section 3.5). The P1 curve (blue curve in Fig. 3.8.4) shows two main phases of thickening (54-39 Ma and 33-6 Ma). The time in between thickening phases corresponds to the initiation of strike slip faulting (S1; 38 Ma). As the slip rate of S1 decreases (Section 3.5), the P1 thickening curve slowly increases between 34 to 10 Ma. The second decrease in the P1 thickening curve at 6 Ma corresponds to the beginning of the second phase of strike-slip faulting (S2). Thus, P1 is strongly related to the strike-slip faulting: S1 starts as the first phase of thickening ends, and S2 starts when the second phase of thickening ends.

The P2 curve (green wave in Fig. 3.8.4) seems to be generally related to the thrust faulting events (related to the progressive formation of five sub-plateaus). Four (T1, T3, T4 and T5) of six thrust faulting events coincide with P2 peaks. Finally, the P3 curve (purple wave in Fig. 3.8.4) has peaks that coincides with two (T2 and T6) of six thrust faulting events. This curve is more or less flat between 35 and 18 Ma and after 6 Ma, coinciding with periods where strike-slip faulting is dominant. This suggests that the thickening and strike-slip faulting motion was alternating at this time-scale (~ 4.2 Myrs) before 35 Ma and between 18 and 6 Ma.

Based on our analysis, we suggest that P1 represents the two extrusion phases, 27 Myrs. The P1 curve generally agrees with phase S1 (38-10 Ma), which represents the development of the Red River fault (35-16 Ma (Peltzer et al., 1989; Tapponnier et al., 1990; Briaies et al., 1993; Leloup et al., 2001; Tapponnier et al., 2001; Replumaz and Tapponnier, 2003)), and with phase S2 (6 Ma- present), which represents motion on the Altyn Tagh fault. P2 represents the dominant period of thrusting that thickens the plateau, 11 Myrs. This curve coincides with four of six thrust events. This period is consistent with the concept of a progressively generated Tibetan plateau [Tapponnier *et al.*, 2001]. Furthermore, we suggest that P3 also represents thrusting events on a shorter time-scale, 4.2 Myrs. Even though P3 has peaks that coincide with two of the six thrust events, the main observation is that there is no thickening between 35-18 Ma. This coincides with the period of fast S1 propagation as well as with the opening of the South China Sea (32-17 Ma; (Taylor and Hayes, 1980, 1983; Leloup et al., 2001)).

Fig. 3.8.1. Indentation volume change, vertical deformation change and horizontal deformation change each 0.15 million years.

Fig. 3.8.2. Illustration of the indentation and vertical volume change during the moment interval between moment 1 (M1) and moment 2 (M2). Between M1 and M2, indentation and vertical volume change are the volume sum of spherical elements which are located in the gray zone and in the orange zone respectively.

Fig. 3.8.3. Period domain of the vertical deformation change data. Red box, period range from 2.56 to 54 Myrs includes all dominant period peaks from the data; blue box, period range from 13.89 to 54 Myrs, including the first peak, P1;

green box, period range from 6.9 to 13.89 Myrs, including the second peak, P2;
purple box, period range from 3.7 to 5 Myrs, which comprises the third peak, P3.

Fig. 3.8.4. Primary components of the vertical deformation change data (P1: 27 Myrs; P2: 11 Myrs; P3: 4.2 Myrs). Timing of strike-slip and thrust faulting events is taken from Section 3.5.

3.9 Conclusions

In this chapter, we review the main geological features in Asia, caused by the India-Asia collision. We discuss the slip rates and offset amounts along strike-slip faults around the Qinghai-Tibet plateau. We also discuss the plateau generation with thrusting and strike-slip faulting on the Qinghai-Tibet plateau. After developing an understanding of the geological features in Asia, we construct the 3D DEM model. Following to the parameter testing and validation in the previous chapter, we set reasonable parameter configurations for the 3D model.

Before the 3D simulation, we need to understand the mechanical behavior of the material which we use to conduct the modeling. In order to understand the mechanical behavior, we perform both uniaxial compression and direct shear tests. We then analyze stress-strain curves from these two tests. We determine the strength of the material and the residual strength after the yield stage. We also obtain the strength of the fault in the material from the direct shear test. Combining these findings we can understand the general strength of the entire model.

In addition, we have to scale our model with respect to gravity. Using the scaling equation, we obtain that the scale value for the model is of same order of magnitude for the real lithosphere. In order to get a reasonable and comparable amount of deformation, we also test the effect of gravitational acceleration. Furthermore, we discuss the different strength of the interface between the indenter and the model, which could correspond to the friction between the Indian and Asian plates. We determine that the slip of the Altyn Tagh fault along the Himalayan range may be accounted for by lower friction or strength at the interface of the collision zone.

In 3D simulation, we analyze the crack distribution, kinematic models, semi-kinematic models, displacements along the west-east, north-south and vertical directions, cross-sections, and combination views of horizontal and vertical deformation. We identify the thrust faults, plateau zones and strike-slip faults. We also investigate the rotation of the separated block as well as its rotation role. Furthermore, we depict the maximum and average thicknesses of

the deformed lithosphere under the plateau. By recording the thickened and shortened volumes, the ratio of the total thickened modeled lithosphere to the total shortened volume at the different scaled times can be calculated. The plateau generation process matches the concept of the oblique stepwise rise and the growth of the Tibet plateau. The size, uplift of the plateau, the faulting patterns, the total offset amounts, and slip rates along the strike-slip faults either in the plateau or around the plateau are consistent with observations. This is the first time that we are able to reproduce a comparable plateau generation and consistent strike-slip faulting together in the collision zone.

Furthermore, we propose an efficient approach to determine the focal mechanisms of micro seismic events occurring between the spherical elements. The micro focal mechanisms help us describe the fault and also provide us information about the alternation between thrusting and strike-slip faulting.

Finally, we quantitatively analyze the oscillation between thrusting and strike slip faulting in the collision process. Even with the constant indentation volume change, the alternation of thickening and strike-slip faulting is conspicuous. We use the Fast Fourier transform to obtain the periods of the different orders of thickening, and use the Butterworth function to filter the signal with different periods. From the thickening signal analysis, the period of the strike-slip faulting is about 27 Ma and the thrusting period is about 11 Ma. One more period of 4.2 Million years shows a second-order thickening is also apparent while thrusting is dominant. However, very little second-order thickening is apparent during strike-slip faulting. In particular, during the period when the

zone corresponding to the South China Sea is opening, there is no second-order thickening. This feature shows that the strike-slip faulting is overwhelmingly dominant even when combined with the first-order thickening action.

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Chapter 4 Necking and Fracking Account for Stationary Seismicity and Full Degassing in Silicic Spine Extrusions

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Introductory/Summary Paragraph

Volcanic seismicity during silicic spine eruptions often involves recurrent excitation of similar sources at stationary depth beneath active domes. The mechanics of volcanic spine extrusion is comparable to that of high-temperature metal working. We thus use Slip-line Field theory to assess stress, strain and faulting in hot -albeit solid- ascending magma. Earthquakes fault-plane solutions during the 09/2004-08/2005 eruptions of Mount St. Helen's are consistent with shrinking of

magma rising across a conduit “bottle-neck”. Amidst more than 210 mechanisms, thrust and vertical fault planes prevail, with fewer normal or strike-slip faults. Constriction across the neck and vertical shear along the conduit walls thus predominate. Dynamic Discrete Element Modeling (YADE code) validates repetitive nucleation and growth of thrust faults within such a neck. The pressure drop across the neck’s core (secondary tension) boosts crack opening and hence gas extraction. Such natural “fracking” promotes full degassing inside the spine, accounting for the typically low explosivity of silicic eruptions.

4.1 Introduction

Volcanic seismicity (including Low-frequency, LFVS: 0.2Hz to 10Hz) is common during silicic dome and spine extrusions (Supplementary Fig. 4.S1). The events, which include multiplets, repeat during periods lasting minutes to weeks (Neuberg et al., 2006; Pallister et al., 2013). The source types range from drumbeat (low-frequency, hybrid) to volcano-tectonic (VT) [e.g.,(Moran et al., 2008)]. The regular occurrence, mostly in swarms, of such events is thought to reflect the periodic excitation of repeatable, “non-destructive” sources. Many hypocenters are commonly located beneath the active domes at fairly constant depth (Lahr et al., 1994; Neuberg et al., 2006), (Figure 4.1, Supplementary Fig. 4.S2).

Understanding the mechanics of such volcanic earthquakes is important to elucidate eruptive processes and to assess related hazards. This, however, is a challenging goal because of the co-involvement of multiphase (gas/liquid/solid) thermal effects, large changes in physical properties (strength, viscosity, density), and magma flow geometry/kinematics (Ramos et al., 1999; Chouet, 2003; Chouet and

Matoza, 2013). Cracking along the conduit walls likely accounts for final gas escape at the crater rim (Jellinek and Bercovici, 2011), but not for restricted event depths and full magma degassing. Abundant brittle-ductile deformation textures in silicic lavas imply fracturing/faulting within the magma itself (Tuffen and Dingwell, 2005; Green et al., 2006; Neuberg et al., 2006; Tuffen et al., 2008; Thomas and Neuberg, 2012; Vargas-Bracamontes and Neuberg, 2012; Pallister et al., 2013; Kendrick et al., 2014), which must thus behave as a solid, but studies at Montserrat and Mt St Helens suggest that this occurs primarily near the conduit edges, where the hot magma shears past cold host rock (Heiken et al., 1988; Jousset et al., 2004; Green et al., 2006; Chouet and Matoza, 2013; Pallister et al., 2013; Kendrick et al., 2014). If distributed along much of the conduit height, however, such lateral faulting would not account for the stationary depth of many of the earthquakes (Figure 4.1, Supplementary Fig. 4.S2). Increased lateral shear due to a narrowing conduit (Thomas and Neuberg, 2012), could trigger lateral faulting past the corresponding constriction, but such a geometrical change would not account for the decline or termination of such faulting farther upwards.

Changes in conduit width, however, which are likely, do suggest simple mechanisms that may simultaneously explain stationary, albeit recurrent, faulting and degassing within hot, albeit solid, magma as it forces its way across a restricted path. Here, we show how earthquake fault plane solutions from the 2004-2005 Mt. Saint Helens spine eruption (Moran et al., 2008) support this mechanism, which is further validated by both theory (Johnson et al., 1970; Backhofen, 1973) and discrete element modeling (Jiao et al., 2014).

4.2 Eruptive volcanic seismicity

Volcanic seismicity spans a broad spectrum ranging from tremor to high frequency hybrid earthquakes (McNutt, 2002; Chouet, 2003; Chouet and Matoza, 2013), with signals varying from continuous to periodic. Hybrid and low-frequency (LF) events have been simply interpreted to have similar sources but different sizes (Horton et al., 2008). All these diverse events commonly occur in swarms, coevally with degassing (Tuffen and Dingwell, 2005; Tuffen et al., 2008; Pallister et al., 2013).

The typical structural settings of two well-studied volcanic swarm sequences, in the Caribbean and Cascadia respectively, are shown on Figure 4.1. For the June 19-20, 1997 Soufriere Hills swarms in Montserrat, most of the events occurred at depths between 1 and 1.3 km beneath the ≈ 1 km wide crater center (station MBGA (Neuberg et al., 2006)). Within uncertainty, the hypocenters were located just above the projected depth of the seafloor upon which the volcano is built (Figure 4.1a). The complex geometry of Soufriere Hills in map-view and section results from oblique faulting across the northwest flank of the active dome, and from glacially driven sea-level change (Le Friant et al., 2009; Feuillet et al., 2010).

For the thoroughly documented 08/2004-08/2005 eruptive sequence of Mount St. Helens (Figure 4.1b, c, and Supplementary Figs. 4.S1 and 4.S2), (Horton et al., 2008; Moran et al., 2008; Qamar et al., 2008; Thelen et al., 2008), a wealth of complementary evidence is available. That eruption produced oblique, SE- to SW-wards extrusion of tilted, so-called “whaleback” spines, up to 460 m long (Supplementary Fig. 4.S1). Volcanic seismicity swarms accompanied the extrusions, with most of the events located at depths between 0.6 and 1.4 km beneath the crater

floor, within a 1.2–2 km broad zone right underneath the center of the ≈ 2.3 km wide crater rim (Figure 4.1b, c, Supplementary Fig. 4.S2). Despite depth uncertainties of a few hundred meters, many earthquake hypocenters appeared to cluster near 1000 m asl, a level corresponding roughly to the average elevation of the Cascadia plateau upon which the volcano is built (Figure 4.1b, c, Supplementary Fig. 4.S2). Both examples illustrate a common feature of volcanic seismicity swarms: they often occur at steady depth beneath the center of the crater within which the spines/domes extrude, implying a causative link (Neuberg et al., 2006; Thelen et al., 2008; Thomas and Neuberg, 2012).

The origin and mechanisms of volcanic seismicity (including LFVS) are not fully understood. It is generally thought to result from faulting in both the cold host-rock and the brittle-ductile outer edge of the ascending/degassing magma sheared along the conduit walls (Lahr et al., 1994; Chouet, 1996; Voight et al., 1998; Neuberg et al., 2006; Thomas and Neuberg, 2012; Pallister et al., 2013; Kendrick et al., 2014). Yet, while boundary shear and gas extraction undoubtedly play an important role, they do not suffice to account for the variable mechanisms of volcanic earthquakes, their frequent occurrence at fairly constant depths, and the full degassing of the andesitic spines.

4.3 Earthquake mechanisms during Mt St Helens spine extrusions

One of the most comprehensive dataset documenting volcanic seismicity during silicic-spine extrusion is that of the 2004-2005 eruptions of Mt St Helens (Horton et al., 2008; Moran et al., 2008; Qamar et al., 2008; Thelen et al., 2008). Moran et al. (Moran et al., 2008) determined fault plane solutions for 215 distinct

events (Supplementary Fig. 4.S3 and 4.S4). The magnitudes of these events range between 0.5 and 3.5, with an abrupt cut-off at about $M \approx 3.25$ (Supplementary Fig. 4.S3). That cut-off may be interpreted to reflect the maximum possible source length, which would then be on order of 100 meters (personal communication Shengji Wei). As common in similar volcanic seismicity studies, not all the focal mechanisms are simple double-couples, likely due to source complexity, and many suffer from sparse arrivals at the center of the focal sphere (Supplementary Fig. 4.S4 and 4.S5). Nevertheless, most of the solutions are of good quality, and we use them here at face value to clarify deformation mechanisms beneath the crater. The faulting patterns that emerge from this exceptional dataset are shown in Figure 4.2 and Supplementary Fig. 4.S6. The P/T axes orientations (equal area projection) of individual focal mechanisms from the entire sequence suggest that the earthquakes may be separated into 4 distinct groups (Figure 4.2).

The dominant mechanisms (99 events, 46% of the total, Figure 4.2a) correspond to thrust faults, likely near or in the conduit. The thrust-slip directions are fairly uniformly distributed, but with second-order maxima oriented NNW and NNE (Supplementary Fig. 4.S6a). The next most common solutions (68 events, 31%, Figure 4.2b) correspond to vertical slip, plausibly along the conduit rims [e.g., (Thomas and Neuberg, 2012; Pallister et al., 2013)]. At a more detailed level, the distribution of the nodal planes is also non-uniform, with symmetry about a N-NNW striking direction (Figure 4.2b and Supplementary Fig. 4.S6b). The remaining two groups of mechanisms concern less frequent events, adding up to only 1/4th of the total. They include normal (30, 14%, Figure 4.2c) and strike-slip faults (19, 9%,

Figure 4.2d) events. The null vectors of the strike-slip mechanisms are roughly aligned E – ESE (Figure 4.2d and Supplementary Fig. 4.S6d).

The deformation processes and structural settings of faults likely to account for the earthquake mechanisms are sketched in Figure 4.3. The dominant thrust mechanisms indicate horizontal, essentially radial shortening. Shrinking of the solid spine as it rises through a conduit “bottle-neck” (Figure 4.3a), is the most plausible way to account for such shortening. The hot, solid spine magma would be weaker than the colder surrounding host rocks, and thus faulting would occur mostly inside rather than outside the spine. Conduit bottle-necks are likely to exist beneath the craters of both Mt. St. Helens and Soufrière Hills at the base of the volcanic edifices (i.e., 1 to 1.5 km deep, Figures 4.1 and 4.3a). At such depths, the spine would ascend across a sharp geological contact between old, weathered and young, stronger rocks (in Cascadia: Oligo-Miocene volcanic bedrock and Pleistocene dacites; In Montserrat: Tertiary pelagic sediments and Quaternary andesites), which would likely correspond to a taper from wider to narrower conduit. Across such a neck, the ascending magma (e.g., 1902 spine of Mt. Pelée in Martinique, or 2004-2005 spines of Mt. St. Helens; Supplementary Fig. 4.S1) would have to contract horizontally and radially, while expanding vertically. Such shrinking/extension would take place only at the passage across the neck, accounting for both the stationary depths of many events (Figure 4.1), and for the apparent “periodic excitation of repeatable, non-destructive sources”.

The second most frequent mechanisms (Figures 4.2b and Supplementary Fig. 4.S6b) are best interpreted to reflect vertical shear along the conduit walls during the upward ascent of the spine (Figure 4.3b), as commonly inferred and recently

validated in situ (Pallister et al., 2013). The second-order symmetry of the P and T axes distribution suggests that the shape of the conduit might be elliptical about a long axis trending $\approx N10 \pm 5^\circ E$ (Figures 4.2b and Supplementary Fig. 4.S6b). This direction is similar to those ($N 5$ to $14^\circ N$) of young volcanic alignments and eruptive dikes (Indian Heaven, Three Fingered Jack, Two Sisters) south of Mt St Helens. It is thus consistent with the regional extension and minimum horizontal stress directions ($N 95$ - $104^\circ E$) in northern Cascadia [e.g., (Zoback and Zoback, 1980)].

The less frequent normal fault events (Figures 4.2c and Supplementary Fig. 4.S6c) may also be related to shear along the spine walls, but at various levels of the conduit. Magma rise on the inward-leaning sides of the neck would generate normal faulting (Figure 4.3a). So would, at very shallow depth, shear on the downside of the inclined whaleback spines (Figure 4.3e). At greater depth, lateral inflation of the magma chamber due to increased magma pressure might trigger normal-fault collapse of the host rock in the chamber roof (Figure 4.3c), though the available 2004-2005 St Helen dataset is too shallow to test such a mechanism. The first two processes, however, may account for the solutions shown in Figures 4.1c and 4.2c and Supplementary Fig. 4.S2c and 4.S6c.

The least abundant strike-slip mechanisms (Figure 4.2d and Supplementary Fig. 4.S6d) probably reflect local horizontal shortening and shear of the host rock outside the conduit, due to non uniform inflation of its wall by magma pressure (Figure 4.3d). Although vertical planes containing the majority of the null vectors are roughly perpendicular to the $\approx N10 \pm 5^\circ E$ orientation, which coincides with the average surface extrusion direction of the whaleback spines (Supplementary Fig.

4.S6d), the events population is insufficient to assess their relationship with both ambient stress and magma extrusion.

4.4 Stationary seismic Necking, Fracking and spine degassing

The deformation of a hot, solid volcanic spine ascending across a conduit restriction is mechanically identical to that documented during industrial shaping of hot metal rods (Blickwed.Dj, 1970; Backhofen, 1972, 1973; McVeigh and Liu, 2006). Figure 4.4 shows the analytical plane-strain slip-line field expected for extrusion through a frictionless, wedge-shaped neck (or die) of small reduction (Blickwed.Dj, 1970; Backhofen, 1972, 1973; McVeigh and Liu, 2006). The orthogonal slip-lines are conjugate, maximum shear-stress trajectories, corresponding to the most likely newborn faults. Because their positions are fixed relative to the neck boundaries, they typically materialize in the form of similar, repeatable faults at that steady position within the moving spine. This simple mechanism can thus generate large numbers (swarms) of repeatable, nearly identical, stationary earthquakes - including multiplets -, accounting for the apparent “periodic excitation of repeatable, non-destructive sources” noted in most studies. The high temperature of the ascending magma, close to the brittle/ductile transition, would be in keeping with the variable event types (drumbeat, low-frequency, hybrid, VT...). Except for the tapered edges of the neck and the lateral sides of the basal slip-lines, which generate normal faulting, the majority of the slip lines correspond to thrust faults that accommodate shrinking of the spine as it is forced through the narrower conduit neck (Figure 4.4). Uniform, relatively weak friction along the spine walls would not significantly change such slip lines and faulting patterns (Blickwed.Dj, 1970; Backhofen, 1972, 1973; McVeigh and

Liu, 2006). Nor would the shift from planar to radial strain (Blickwed.Dj, 1970; Backhofen, 1972, 1973; McVeigh and Liu, 2006). The overall fault distribution, geometry and mechanisms predicted by the spine necking model of Figure 4.4 thus account well for the three main types, and relative abundance, of earthquake focal mechanism documented at Mt St Helen (Figures 4.1, 4.2 and Supplementary Fig. 4.S2c and 4.S6).

There is additional, direct evidence for the existence of predominant thrust faults within the spine interiors at Mt St Helen. Night-time infrared photographs of the largest emerging whaleback spine (Spine 3, 29 November 2004, 10m/day), (Horton et al., 2008; Moran et al., 2008; Qamar et al., 2008; Thelen et al., 2008), clearly image, at the emerging base of that spine, several fault zones that crosscut its entire roof (Supplementary Fig. 4.S7 and 4.S8). Because these faults act as conduits for hot gas escape, their detailed geometry and kinematics are brightly outlined. They do not offset the spine surface, which requires that they formed at depth within the interior of the spine, where it was still bounded by the conduit walls. That the intersections of the fault planes with the spine walls rise and curve back down from west to east (Supplementary Fig. 4.S7 and 4.S8b) indicates that they originated as south-dipping surfaces inside the then vertically ascending spine. As illuminated by the hot escaping gases, the four clearly exposed, sub-parallel faults appear to be composed of right-stepping cracks (Supplementary Fig. 4.S1a and 4.S7). This is consistent with thrust faulting inside the rising spine, before it was tilted southwards during emergence. Note that, since limited by the total width of the spine, such thrust faults may only be at most $\approx 100\text{m}$ long (Supplementary Fig. 4.S7b), hence capable of

generating earthquakes with maximum magnitudes of ≈ 3 -3.5, in keeping with those observed in the 2004-2005 sequence (Supplementary Fig. 4.S3).

The necking deformation process shown in Figure 4.4 likely also accounts for the nearly complete degassing of silicic spine interiors, which remains incompletely understood. Necks with relatively small reduction (i.e., moderate lateral shrinking relative to conduit width) produce fairly large confining-pressure drops inside the material that is forced across them (Hencky's law, [e.g., (Backhofen, 1972, 1973)]). Such normal-stress drops ("secondary tension") increase towards the center of the neck, which commonly suffices to crack open weak, brittle material [e.g., (Blickwed.Dj, 1970; McVeigh and Liu, 2006)]. Open cracks develop more densely at the center of the spine, in the maximum tension area where the symmetrical slip-lines meet (Figure 4.4), and propagate on either side, providing continuous gas-escape paths to the conduit edges. Secondary tension may thus be the most efficient mechanism to generate both swarms of internal micro-cracks and open lateral faults, i.e. connected, multiscale pathways for penetrative magma degassing within ascending solid spines. The whole physical process is a natural equivalent of industrial "fracking", a well understood and widely used technique to retrieve captive hydrocarbons in tight reservoirs. Note that pervasive internal degassing would further accelerate cooling and hence augment the brittleness of the magma. Loss of volatiles - notably water - has a huge effect on solidus temperatures of silicic magmas (Burnham, 1979; Cashman and Blundy, 2000). Hence, cracking and related degassing should have a runaway effect on spine crystallization and solidification.

4.5 Discrete element modeling of faulting across a spine neck

The detailed mechanisms of faulting within a weak solid spine ascending through a conduit restriction inside stronger bedrock at fixed depth may be further investigated with Discrete Element Modeling (DEM) (Cundall and Strack, 1979; Donzé et al., 1994; Hardy et al., 2009; Scholtès and Donzé, 2013). We use the YADE DEM code (Kozicki and Donzé, 2009), which is ideally adapted to explore the deformation of various geo-materials, including, most importantly, strain-localization into shear-zones or faults.

With a simple square model under uniaxial compression, we first calibrate the code's physical parameters appropriate for faulting in a brittle-plastic magma (Supplementary Fig. 4.S9), (Scholtès and Donzé, 2013). Strain softening (Supplementary Fig. 4.S9 left) is essential to localize shear and initiate faulting (Supplementary Fig. 4.S9 top and bottom right). Based on the calibrated parameters, Figure 4.5 then shows, in plane strain, for simple neck geometries and with zero or low friction along the conduit-walls, the evolving stress and strain fields, and the birth and growth of faults in and above the conduit neck. The striking resemblance between faults and cracks in the DEM model and in the emerging St Helen 2004 spine 3 is shown in Supplementary Fig. 4.S8 a and b.

In all 4 models, the magma ascending past the shrinking conduit is fractured by constriction, with thrust faulting along the maximum shear stress trajectories (micro-cracks, shear force, Figure 4.5), in keeping with slip-line field theoretical predictions (Figures 4.4). The thrusts are repeatedly renewed in stationary position within the moving magma. For reductions in conduit width of less than $\approx 20\%$ over

similarly short lengths (Figure 4.5 b and c), the hydrostatic pressure (normal force) drops in the middle of the conduit, past the neck, as required by the upward increase in extrusion rate. This “secondary tension” (Johnson et al., 1970; Backhofen, 1972) drives the vertical opening of shallow-dipping/horizontal cracks. In the natural environment, such cracks (Supplementary Fig. 4.S8) would readily extract gas from the magma (natural “fracking”), and might also resonate seismically. Even though the simple DEM approach we use here is 2D (plane strain), none of the main results would be altered by cylindrical geometry. Similarly, introducing plausibly small friction coefficient values along the conduit walls would have only minor effects on faulting inside the spine (see deformation kinematics and normal force, Figure 4.5). Note that, in any event, the strong degassing generally observed along spine conduit walls, which implies efficient, steady fluid escape, requires very limited interface contact, hence friction.

4.6 Conclusion

Many of the earthquakes recorded during Mt. St. Helen’s 2004-2005 eruption occurred beneath the crater, at shallow, roughly stationary depths ($\approx 1 \pm 0.4$ km). They show two principal types of focal mechanisms. Besides the abundant events that reflect slip along the conduit walls, the most frequent earthquakes ($\approx 50\%$) imply thrust faulting. This pattern may be typical of volcanic seismicity during silicic spine ascent in general.

We propose that the dominant events are repeatedly triggered at steady locations inside the rising, solid magma, where it is compressed laterally and stretched vertically while passing across a conduit bottleneck. The vertical tensile

stresses (secondary tension) generated inside the magma by such “necking” cause the opening of $\approx$ horizontal/shallow-dipping, penetrative cracks within the spine, allowing for full, pervasive gas extraction (“fracking”). The internal cracks also efficiently feed gas escape along the conduit walls. Fracking due to necking would thus explain the remarkably effective, penetrative loss of volatiles that contributes to foster magma solidification in ascending spines. Additionally, fluid infilling of opening cracks might account for low frequency seismic resonance. Simple dynamic modeling (DEM) validates the formation of thrust faults and open cracks within a conduit neck of small reduction, as also observed in the shaping of hot metals and predicted by slip-line field theory.

The interrelated mechanisms we describe here are triggered by simple, hence probably common, changes of conduit geometry that can be readily linked with local, shallow crustal structure and geological history. Besides illuminating the focal mechanisms of many volcanic seismicity events, necking is consistent with a broad zone of renewable, stationary faulting within the conduit, as observed beneath the crater, rather than mostly along the conduit walls, which would result in hollow circular distributions of epicenters. Fracking provides a superior mechanism for extracting gas out of solid magma, and hence contributes to elucidate the hitherto puzzling non-explosive nature of silicic spine ascent. Further testing of such dual, necking/fracking processes should be a primary target of instrumental studies of future spine eruptions.

Figure 4.1 / Volcanic seismicity (a) Top left: topography and bathymetry of Soufrière Hills and Montserrat. Bottom: Soufriere Hills's south-side topographic profiles A1-A2 and A2-A3, and location of 53 seismic swarm events (solid red circles with thin error bars, June 1997, from (Neuberg et al., 2006)). Swarm is positioned under crater (A2), with rough location, and depths extracted from Figure 4.2d in

(Neuberg et al., 2006). Gray solid line: present sea-level. Dotted-dashed line: last glacial-maximum low-stand. Dashed line (~ 1.3 km beneath crater): average sea-floor depth around volcano, projecting just beneath seismic swarm. **(b)** Top left: topography of Mt. Saint Helens and adjacent Cascadia plateau, Washington. Bottom: topographic profiles A1-A2 and B1-B2 across volcano, and 2D distribution of 215 volcanic seismicity events (24/09/2004- 27/08/2005, solid red symbols with thin error bars) from (Moran et al., 2008). Densest volcanic seismicity swarm lies near volcano baseline (violet dashed, ~ 1.2 km below crater). **(c)** 161 volcanic seismicity events (24 September to 10 October 2004). Symbol sizes reflect events magnitudes (0.1 to 3.6).

Figure 4.2 / P and T axes (open and solid circles, respectively) plots of 216 seismic events, from fault-plane solutions of (Moran et al., 2008) of USGS, 2008. **(A)** 46%, thrust faults, **(B)** 31%, vertical faults, **(C)** 14%, normal faults, **(D)** 9%, strike slip faults. Red: good quality solutions; Orange: acceptable; Yellow: poor quality; Green: all tension points; Blue: null vectors. Red solid lines: maximum horizontal stress directions (containing P and T) from volcanic alignments south of Mt. St. Helens (Indian Heaven, Three Fingered Jack, Two Sisters).

Figure 4.3 / Plausible volcanic seismicity sources. Small arrows beneath volcano: ascending magma pressure (left column). Square lines (left column): locations of potential seismic sources blown up in right column. Black stars (right column): event epicenters. Half arrows (right column): fault-slip directions. Beechballs on right side show events focal mechanism: **(a)** Thrust faulting: spine constriction in conduit neck. **(b)** Vertical slip of spine along conduit wall. **(c)** Bedrock normal faulting due to collapse of expanding magma chamber roof. **(d)** Bedrock

strike-slip faulting due to non-uniform magma pressure in conduit. **(e)**

Normal/thrust faulting on conduit walls of shallow tilted spine.

Figure 4.4 / Slip-line field for extrusion through small reduction neck (after (Johnson et al., 1970)). Bold red lines: spine conduit walls. Large, full orange arrows: spine ascent rate. Red/black thin curves: slip lines (maximum shear stress trajectories). Violet triangles: “dead” zone. Violet, orange, and green double arrows: thrust, vertical, and normal faults, respectively. Yellow elliptic zone at center of field: secondary tension area of fracking and gas extraction. Thick yellow lines: upward gas escape pathways.

Figure 4.5 / Discrete Element modeling of spine deformation (plane strain) across 4 different conduit necks. **(A)** lower/upper conduit widths: 5 and 2 m, respectively. Neck length: 2 m. Reduction angle: 37°. **(B)** lower/upper conduit widths: 5 and 4 m, respectively. Reduction angle: 37°. **(C)** lower/upper conduit widths: 5 and 4 m, respectively. Neck length: 2 m. **(D)** Neck size and geometry as in (A), with friction along

upper conduit walls. Boundary conditions: Top of conduit is open, lateral walls, rigid. Rate of rigid plate rise at base of spine is 10^{-3} m/s. Conduit walls are frictionless except in and above neck in (D). For normal force (N), compression/tension are positive/negative, respectively. Physical parameters: Young's modulus, 3×10^5 Pa; α (related to Poisson ratio), 0.004; Friction angle, 0; Tensile strength, 1×10^3 Pa; Cohesion, 1×10^3 Pa; K (coordination number, which controls brittleness), 10; and S (weakening gradient), 10; Total healing.

Appendix of Chapter 4

Supplementary Figure Captions

Supplementary Figure 4.S1 / Large Silicic spines (a) Emerging 2005 Mt. St. Helens “whaleback” spine 4 (Pallister et al., 2013). **(b)** November 1902 solid, vertical spine of Montagne Pelee (Photograph by Alfred Lacroix).

Supplementary Figure 4.S2 / St. Helens volcanic seismicity (from (Qamar et al., 2008; Thelen et al., 2008)). **(a)** 4 months (2004) of volcanic seismicity below Mt. St. Helen's vent. Red circles with location error-bars are individual events. Triangles are local seismic stations **(b)** Section (dashed line in **(a)**) displaying events depth distribution shows ≈ 1.5 km deep swarm beneath crater. **(c)** 24/09/2004 - 27/08/2005 events (215) sequence plotted as a function of number and depth. Symbols and colors as in Figure 4.1. Many events lie $\approx 1 \pm 2$ km below crater. **(d)** Complete record of 1980 to 2006 Mt. St. Helen volcanic seismicity. Timing of sequence shown in **(c)** is outlined in yellow. Also note long-term concentration (shaded) of events $\approx 2.3 \pm 0.7$ km deep.

Supplementary Figure 4.S3 / 215 earthquakes magnitudes distribution (binned).

Note regular increase of event abundance up to sharp cut-off at $M \approx 3.25$.

Supplementary Figure 4.S4 / Selected examples of fault plane solutions of 215 sequence, from appendix in Moran et al., USGS, 2008. Note paucity of first arrivals in center of nodal sphere.

Supplementary Figure 4.S5 / Fault-plane solution (FPS) quality assessment [from (Moran et al., 2008)]. **(A)** Good quality: all P and T first motion arrivals separated by nodal planes. **(B)** Lesser quality, partly non double-couple component. **(C)** Dilatation arrivals only. Bottom shape/color symbols refer to 3 event quality types (Figures 4.1c, 4.2, 4.S2c and 4.S6).

Supplementary Figure 4.S6 / Comparison of σ_1 - σ_3 (P-T) stress-tensor principal-planes, consistent with FPS types in Figure 4.2, with horizontal, regional tectonic stresses. σ_1 - σ_3 great-circles (lines) connecting P and T axes (dots) are colored as in Figure 4.2. Purple/Cyan lines are regional bounds of maximum/minimum horizontal stresses directions. Shaded light-grey quadrant is range of whaleback spine extrusion directions.

Supplementary Figure 4.S7 / Exhumed, deep thrust faults in Spine interior. (a), (b) Enlarged Thermal-Infrared images of St. Helen's spine-3, 29/11/2004 (Schneider et al., 2008; Vallance et al., 2008), viewed towards south and east, respectively. Bright orange/yellow crack alignments are conduits of active gas-escape marking faults dipping into the spine. **(c), (d)** Interpretation of images (a)/(b): Cracks right-stepping, "en-echelons" arrangements (light-orange) are consistent with thrust faulting (small arrows) inside spine (pale-pink) when extrusion ascent (large white arrow) is restored to vertical.

Supplementary Figure 4.S8 / Comparison of brittle crack opening in DEM and Infrared image. **(a)** Zoomed modeling results (shear force, B, figure 4.5). **(b)** 29/11/2004 Spine-3 faults, viewed from above-north.

Supplementary Figure 4.S9 / Cubic, uniaxial compression test for modelling calibration. Left: Stress-strain curve of model Spine-material. Top-right: shear force

localization at 25% strain. Bottom-right: Faulting and bulk deformation, outlined by alternate, colored element layers, for same amount of strain (See references in text for modeling method, and algorithm/parametrization).

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Author Contributions:

P. Tapponnier defined the research subject/project, which was undertaken by L. Jiao under the joint guidance of F. Costa. F. V. Donzé introduced L. Jiao to the numerical method/code, which she adapted to the problem under the supervision of L. Scholtès. L. Jiao performed the synthetic analyses of Mt St Helen's seismicity and conducted the numerical modeling as part of her PhD-Thesis research. L. Jiao, P. Tapponnier and F. Costa wrote the paper. All authors contributed to scientific discussion and critical validation of results.

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Chapter 5 Conclusions and perspectives

Our exploration of the use of the DEM technique to model both large and small scale faulting in different contexts gives us good hope to address and solve complex geological problems involving faulting in active tectonic and volcanic environments. We used one of the best DEM coding platforms, namely the Yet Another Dynamic Engine code (YADE) [e.g. (Šmilauer, 2015)]. In order to adapt this code to simulate continental-scale geological deformation (large scale faulting) and silicic volcanic magma behavior (small scale faulting), we modified the micro-contact laws. Using the modified code, we tested the contact bonds in micro-scale and also tested the mechanical behavior in macro-scale.

To simulate large scale faulting, we chose suitable parameter configurations based on batch parameter effect tests, and build up the 2D (plane-strain) model in order to validate the code and parameter configuration. In our 2D collision modeling, we compared the numerical results to earlier plasticine experiments (Peltzer and Tapponnier, 1988), by using an isotropic medium to reproduce the successive extrusion and rotation of two sub-block. The nucleation and propagation of two main strike-slip faults are also observed. The main characteristics of our models including fault pattern, rotation of the sub-blocks and displacement field, are in good accordance with the plasticine model results. The two main strike-slip faults also compare well with the Red River and Altyn Tagh faults. In addition, the rift zones such as the Weihe-Shanxi graben and Ordos block are reproduced. Thus, in our 2D numerical model, all first-order large-scale horizontal deformation and fault zones observed during collision in the Asian

plate are successfully simulated. Note that our DEM modelling technique bears none of the shortcomings that flagged the plasticine experiments (Peltzer and Tapponnier, 1988).

In the 3D simulation, we test the strength of the model, and scale the model with respect to gravity. We discuss the effect of the interface strength between the modeled Indian and Asian plates. The effect of the interface strength shows that a weak interface between Indian and Asian is a key point to account for horizontal slip along the Himalayas. Using the tested parameter configuration, we build up the 3D model. From the simulation results, the growth of thrust faults, plateau zones and strike-slip faults are observed and described together with the crack distribution, kinematic models, semi-transparent kinematic models, east-west, and north-south displacements and vertical thickening. Cross-sections and combined views of horizontal and vertical deformations are also shown. Mainly two large faults comparable to the Red River and Altyn Tagh faults are reproduced, together with the generation of an equivalent of the Qinghai-Tibet plateau. We also analyze the rotation of the separated sub-blocks, and the rotation role of the first sub-block. The two isolated sub-blocks generated by the model are coherent with the existence of the Sundaland and South China blocks. In addition, we investigate the thickness of the deformed lithosphere under the plateau. The modelled thickness of the deformed lithosphere is about two times that in the initial model, which is consistent with the observation of a doubling of the crust in Tibet.

The vertical deformation in the 3D model shows a step by step plateau generation process. This is in agreement with the oblique, stepwise rise and growth of the Qinghai-Tibet plateau model (Tapponnier et al., 2001; Liu-Zeng et al., 2008). This modelled plateau grows northwards, with the successive rise of five sub-plateaus. The sizes and uplifts of the plateaus, the faulting patterns, the total offset amounts, and the slip rates along the strike-slip faults are in keeping with most of those observations in Asia. Importantly, for the first time in any simulation of Asian deformation with any type of modeling technique, change of slip sense, from left to right lateral, is observed on the equivalent Red River fault, as documented along the Ailao-Shan-Red River shear zone (Leloup et al., 1995). These results are unprecedented, as the model reproduces a comparable plateau generation together with consistent strike slip faulting in the collision zone.

In order to depict motions on the different fault-types in the 3D model deformation, we propose an efficient approach to illustrate the micro-focal mechanisms of micro seismic events occurring in the model between the spherical elements. These focal mechanisms account for the fault types, including the alternation of thrusting and strike slip faulting. The focal mechanism distribution confirms that more strike-slip micro-seismic are found along the two strike slip faults that are comparable to the Red River and Altyn Tagh faults, and more thrust micro mechanisms are located in the thrust faults along the edges of the five sub-plateaus.

To better understand the relationship between thrusting and strike-slip faulting in our 3D model, we quantitatively depict the alternation of thrusting and

strike slip faulting motions. Using Fast Fourier transform and the Butterworth function filter, an irregular thickening and volume change signal is filtered, showing two principle thickening periods, and one strike-slip faulting period. The strike slip faulting period is about 27 Ma, while the first and second order thrusting periods are ~ 11 Ma, ~ 4.2 Million years respectively. The strike-slip faulting period is consistent with the development of the two main strike slip faults of east central Asia: the Red River and Altyn Tagh faults. The first-order thrusting period is in keeping with the six large mountain building events that contribute to the sub-plateau growths that together generate the final “Tibet” plateau in the model. It is possible that these mountain building phases correspond roughly to those observed north of India’s Ganges plain: namely; the Himalayas, the Kangdese Shan, the Tangula Shan, the Kunlun Shan, the Qilian Shan.

At a much smaller scale, we use the DEM approach to simulate silicic lava ascent in a volcanic conduit. Indeed, that approach provides a way to reproduce the behavior of a large variety of geomaterials, in which localized shear zones can form. We examine the focal mechanisms of small seismic events that occurred during the spine extrusions of the 2004-2006 eruptions of Mount St. Helens. The recorded 216 events were mostly located at a depth of ~ 1.5 km under the crater. The dominant thrust and vertical faulting mechanisms suggest that frictional magma ascent along the conduit walls and constriction by squeezing past a conduit neck prevail. Using the YADE DEM code and material parameters calibrated to generate localized shear, we model the nucleation and propagation of faults near a conduit neck at fixed depth. The results confirm that constriction fractures the magma itself, leading to faulting along the maximum shear stress trajectories, in keeping with

industrial practice and theoretical predictions. The faults inside the solid magma at fixed depth are principally thrust faults. Moreover, if the reduction in conduit width is less than about 20%, and the neck relatively short, the third principal component of the stress tensor drastically falls in the central part of the conduit, as implied by the upward increase in extrusion rate. This “secondary tension” triggers locally the vertical opening of cracks inside the solid magma. These cracks are able to resonate, and help extract gas from the magma. In addition to secondary tension, the dead zone close to the conduit wall together with the location of the shear zones in the neck are in accordance with Slip Line Field theory and experimental deformation of metals. Moderate friction along the conduit wall does not alter the pattern of cracking of the magma in the neck zone.

Based on our simulations, we conclude that the dimensions of the conduit neck are the most important factor affecting the moment distribution of typical volcanic earthquakes. The secondary tension cracks, together with escape paths along the conduit walls account for degassing and hence magma solidification.

In conclusion, we have shown that the DEM technique is a particularly powerful and promising tool to simulate deformation at radically different scales: several thousands of kilometers for continental collision, and tens to hundreds of meters for eruptive processes.

Challenging problems remain, however. For instance, modelling of continental deformation in the India-Asia collision zone reaches a scale so large ($\sim 5000 \text{ km}^2$) that the model must include a curved lithosphere on the sphere,

which may account for the incongruent amounts of modeled and geologically observed rotations. In the future, we must also involve subduction of the Indian plate, as well as possible block subduction behavior under Tibet. Such an approach might explain why the Qinghai-Tibet plateau appears to be composed of only three sub-plateaus, which might also be more consistent with deep tomographic observations. Finally, this DEM modeling approach may be used to address other tectonic problems within continental or oceanic plates, including rifting and the birth and interaction of extensional faulting. In the volcanic realm, DEM is also a promising approach to simulate volcano collapse, dike propagation and caldera formation. At present the most serious limitation of the technique lies in the total number of elements per model (<500,000) and in computation time. But with progress in both computing time and number of elements, DEM may become in the near future the tool of choice to study the dynamic Earth.

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