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# Mechanical restoration of gravity instabilities in the Brunei margin, N.W. Borneo

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- Gravity-driven deformations
- Mechanical restoration
- Fluids overpressure
- Mechanical modelling
- Brunei delta, Borneo

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Abstract

1

In offshore Brunei, the Baram delta displays Pliocene to recent gravitational deforma-2 tions on top of the overpressured Setap Shales. We use the limit analysis, implemented 3 in SLAMTec, to constrain their kinematics and propose first-order values of compatible pore pressures. Using the critical Coulomb wedge theory, we confirm that extreme overpressure are needed to account for the gravitational deformations currently observed in the delta. SLAMTec simulations quantify the role of the migration of the deltaic system on the deformations and suggest that this overpressure has existed since the initiation of the gravity-driven system. An inverse analysis is performed to identify the fluid overpres-9 sure and sedimentation pattern that best reproduces the forward structural model. This 10 inverse approach validates the proposed kinematics, since we can reproduce quantities de-11 scribing the structural style with overpressure coherent with the present-day observations. 12 It points out the existence of key events explaining the structural interpretations, which 13 leads to propose new kinematic models enriched with compatible pore pressure and sedi-14 mentation rates. This mechanical study highlights how mechanical modelling helps design 15 a cross-section with an appropriate kinematics based on mechanical solutions and discuss 16 on the basis of objective mechanical criteria the ranges of pore pressure consistent with a 17 prescribed structural evolution. 18

## **19** Introduction

Gravity deformations in shelf edge deltas are defined by an upslope extensional domain (growth 20 faults either synthetic or antithetic of the general displacements) and a downslope compres-21 sional domain (Fold and Thrust Belt (FTB)) [see review in Schultz-Ela, 2001; Rowan et al., 22 2004; Morley et al., 2011]. In the Champion-Baram delta, offshore Brunei, Pliocene to recent 23 gravitational deformations are well-identified because of their major interest for the oil and gas 24 industry [Sandal, 1996; Morley, 2003, 2009; Ingram et al., 2004]. While the kinematics of de-25 formation is well-constrained in the Sabah FTB and the northern parts of offshore Brunei [e.g. 26 Franke et al., 2008; Morley, 2009; Hesse et al., 2009, 2010; King et al., 2010; Sapin et al., 2011], 27 more to the south the resolution of the published seismic images is insufficient to decipher the 28 sequence of faults activities, in both extensional and compressional regions [Hesse et al., 2009; 29 King et al., 2010; Sapin et al., 2011]. Without further geophysical and geological information, 30 it is difficult to discriminate one among the different possible model of structural development, 31 which lead to poorly constrain the burial, temperature and stress/strain history of each struc-32 tural block [Sassi et al., 2007; Smart et al., 2012; Albertz & Sanz, 2012; Albertz & Lingrey, 2012; 33 Berthelon & Sassi, 2016]. Ultimately, it leads to uncertainties in petroleum system modelling, 34 seals integrity analysis, pore pressure prediction and stress regime estimation, both because 35 state-of-the-art basin modelling software use prescribed geometries at specific geological times 36 that need prior structural validation [Neumaier et al., 2014; Faille et al., 2014; Thibaut et al., 37 2014; Burgreen-Chan et al., 2016], and because 2-D/3-D fully coupled hydromechanical nu-38 merical simulations are still unable to reproduce complex 2D/3D structural geometries [e.g. 39 Couzens-Schultz & Azbel, 2014; Obradors-Prats et al., 2016, 2017]. 40

We evaluate specific points of the Brunei margin kinematics in terms of mechanical feasibility by requiring them to verify stress equilibrium and the Coulomb criterion for fluid-saturated rocks. We aim to combine mechanical solutions and structural interpretations to improve forward kinematic models, in the manner of Caër *et al.* [2015] and applied on the Brunei margin gravitational collapse system (GCS). We use the limit analysis theory, originally developed to predict the localisation of plastic deformation and plastic failure in civil engineering [e.g.

Salençon, 2002]. The maximum strength theorem [Salençon, 2002; Maillot & Leroy, 2006] 47 corresponds to the kinematic approach of the limit analysis. It has been applied incrementally 48 on compressive tectonics to determine the location and dip of the active ramp thrust and hinge 49 planes at each shortening step, by optimization of the compressive tectonic force [Cubas et al., 50 2008] and further developed into the SLAMTec software (Sequential Limit Analysis Method 51 for Tectonics [Mary et al., 2013a]). Pons & Leroy [2012] accounted for the pore pressure in 52 fluid saturated media. We use here the developments of Yuan et al. [2015, 2016] to account for 53 extensional tectonics and gravitational deformations. 54

Gravity-driven deformations in shale-dominated deltas such as the Brunei margin are con-55 trolled by the strength of the clay-rich detachment that greatly depends on the magnitude 56 of the pore fluid overpressure [Rowan et al., 2004; Morley et al., 2017, 2018], which itself de-57 pends on the stress/strain history, burial and temperature paths and the local fluid flows [Sassi 58 et al., 2007; Beaudoin et al., 2014; Couzens-Schultz & Azbel, 2014; Berthelon & Sassi, 2016; 59 Obradors-Prats et al., 2017]. Elevated overpressures are commonly observed in the Brunei 60 margin [Morley, 2003; Tingay et al., 2009; Morley et al., 2011]. High overpressures within the 61 detachment were shown theoretically and experimentally sufficient to initiate gravitational in-62 stabilities [Mourgues et al., 2009; Yuan et al., 2016; King & Morley, 2017]. Differential loading 63 by deltaic sedimentation between the delta plain and toe is also identified as a major triggering 64 mechanism of gravity-driven deformations in many passive margins [Morley & Guerin, 1996; 65 Vendeville & Cobbold, 1988; Rowan et al., 2004; Mourgues et al., 2009; Rouby et al., 2011; Mor-66 ley et al., 2011]. Deltaic sedimentation is therefore one of the most important phenomenon, 67 since it impacts (1) the differential loading and (2) the production of elevated overpressures 68 through compaction processes and fluid expansion mechanisms such as kerogen to gas or clay 69 transformations [e.g. Swarbrick et al., 2002]. Both quantities (i.e. fluid overpressure and deltaic 70 sedimentation) are therefore important to consider jointly when attempting to design forward 71 models of deformation validated by mechanical tools. 72

In this paper, we select a geological cross-section in the southern Brunei margin and describe
 its structural style, kinematics and boundary forces from up-to-date information available in

the literature. We use the critical Coulomb wedge theory [Dahlen, 1984; Davis et al., 1983; 75 Dahlen, 1990] developed for gravitational collapse with overpressured pore fluid [Dahlen, 1984; 76 Xiao et al., 1991; Wang & Hu, 2006; Mourgues et al., 2014; Yuan et al., 2015] to provide a 77 first estimation of the pore pressure gradients and equivalent effective friction angles of the 78 bulk and detachment materials, as in Bilotti & Shaw [2005]; Yuan et al. [2016]; King & Morley 79 [2017]. Next, we use SLAMTec to determine the fluid overpressure along the bulk material and 80 the detachment  $(\Delta \lambda_b \text{ and } \Delta \lambda_d)$  and the progradation and aggradation of the Plio-Pleistocene 81 deltaic sedimentation that reproduce best the forward structural model (designed according to 82 the geological observations). We then point out the existence of unexpected but key structural 83 and/or sedimentary events to explain the structural interpretations. Consequently, we propose 84 two new kinematic models for the southern part of the Brunei margin, based respectively on 85 variations of the sedimentary input, or on variations in the fluid overpressure found in the 86 detachment. 87

### **Geological settings**

#### <sup>39</sup> Tectonic and litho-stratigraphic context of the Brunei margin

The offshore Champion-Baram basin forms the frontal part of the NW Borneo wedge (Figure 90 1). It is described as a gravity-driven FTB, associated with the deposition of two large post-91 Mid-Miocene deltas, the Baram Delta and the Champion Delta [Sandal, 1996; Ingram et al., 92 2004]. This basin is resting on a continental crust which records a complex accretionnary 93 history resulting from the southward to south-eastward subduction of an early marginal basin, 94 the Proto-South China Sea [Taylor & Hayes, 2013; Rangin et al., 1999; Hall, 2013]. The 95 beginning of the oceanic subduction is dated from the Middle Eocene [Tongkul, 1991], while 96 the convergence zone evolved during the Middle Miocene into a collision zone [Tongkul, 1991; 97 Hutchison et al., 2000; Cullen, 2010; Hutchison, 2010; Sapin et al., 2013]. This transition from 98 oceanic subduction to collison is highlighted by the Mid-Miocene Unconformity (MMU) which 99 forms a major regional unconformity. Continental subduction is thought to be active until the 100 Early Pliocene, as the slab was breaking off [Rangin et al., 1999; Prouteau et al., 2001]. 101

The Champion-Baram basin is formed by a thick pile (>10 km) of early Miocene to Recent 102 clastic deposits, sourced from the rapid erosion of an uplifting mountain range forming in the 103 north-eastern part of Borneo as a result of the subduction/collision [Morley, 2003; Sapin et al., 104 2013]. These sediments form a mainly prograding sequence of cyclic deltaic sand/shale deposits 105 of tidal and shoreface facies [Sandal, 1996; Morley, 2003; Sapin, 2010]. They overlie a thick outer 106 shelf/deep water prodelta shale sequence [Sandal, 1996; Sapin, 2010] usually known as the Setap 107 Formation or Setap Shale (Figure 2b). This shale formation constitutes the main detachment 108 level on which most of the gravity-driven deformations are localised (Figure 2c). This formation 109 was deposited on top of a continental margin which may comprise horst and grabens that lead 110 to lateral facies variations [Sapin, 2010; Sapin *et al.*, 2011]. We consider that, at first order, 111 the thickness of the formation lead to effectively decouple the deformation; This structural and 112 stratigraphic heritage could have nonetheless impacted the subsequent deformations. The Mid-113 Miocene to Pliocene formations could be combined into a homogeneous pile of sediments, in 114 which the Late Miocene Unconformity (LMU) seismic horizon marks the Miocene to Pliocene 115 transition (Figure 2c). 116

The pore-pressure database compiled in the Champion-Baram basin [Tingay, 2003] indicates 117 that overpressured formations are widespread in the area, both in the prodelta shales and 118 the overlying deltaic sediments [Morley et al., 1998; Van Rensbergen et al., 1999; Morley, 119 2009; Tingay et al., 2009]. These overpressures strongly control the mechanical behaviour of 120 the predominant sand/shale facies. Numerous mud volcanoes and shale diapirs highlight the 121 ductile behaviour of the Setap Formation or synchronous shales formations, from the Champion-122 Baram delta to the Sabah FTB [Morley et al., 1998; Van Rensbergen et al., 1999; Sapin, 2010]. 123 The considerable fluid overpressure measured in the basin have been linked to disequilibrium 124 compaction in the prodelta shales [Tingay et al., 2009; Morley et al., 2014]. Tingay et al. 125 [2009] suggest that much overpressure measured in the deltaic sequences have been vertically 126 transferred from the prodelta shale via natural fractures and faults, which does not overruled 127 the fact that fluid expansion mechanism like kerogen-to-gas maturation could have impacted 128 the overpressure build-up, as demonstrated by Morley & Guerin [1996]; Tingay et al. [2013] in 129

other geological settings. 130

The Champion-Baram basin displays structural features typically associated with delta 131 gravity tectonics (growth faults, mobile shale tectonics, toe thrusts) [Morley et al., 1998; Morley, 132 2003; Franke et al., 2008; Morley, 2009; Hesse et al., 2009, 2010; King et al., 2010; Morley 133 et al., 2011; Sapin et al., 2011, 2012], while large scale thrusting and folding and inversion 134 of growth faults reflect episodic phases of compressional tectonic [Sandal, 1996; Morley, 2003; 135 Sapin et al., 2011, 2012]. The margin is characterized by NE to SW variation of the structural 136 style [Cullen, 2010; Sapin, 2010; Sapin et al., 2011], mainly attributable to inherited NE-SW 137 trending accretionary prism structures [Sapin et al., 2009, 2012]. In the north-eastern part of 138 the basin, structural inheritance favours the formation of counter regional normal faults [Sapin 139 et al., 2012, which are inverted in the inner part of the shelf [Morley, 2009; Sapin et al., 2012]. 140 South-westward the paleo-accretionary prism front migrates toward the shelf and the counter 141 regional normal faults tend to fade out in favour of a more conventional gravity-driven tectonic 142 system defined by basin-ward oriented normal faults and toe thrusts (Figure 2c). 143

#### Kinematics of the gravity-driven deformations in the southern part of the Brunei 144 margin 145

We selected a cross-section located in the southern part of the Brunei margin (Figure 2a, c). 146 This cross-section has been interpreted by Sapin et al [2009] from a SE-NW seismic transect; 147 a simple time to depth transformation has been applied, using a constant velocity to depth 148 conversion referring to Morley et al. [2014]. The structural style of the southern part of the 149 Brunei margin can be divided in three distinct provinces, from the SE to the NW (Figure 2c): 150

151

- The inverted province at the extreme SE edge of the section.

- The extensional province in the shelf, in which five major normal faults have been se-152 quentially activated [Sapin et al., 2009; Sapin, 2010]. Three major kinematic steps are 153 defined from the structural interpretation of Sapin *et al.* [2009]; Sapin [2010], establishing 154 a prograding fault activity trend: a first phase sealed by the LMU seismic horizon, a 155 second sealed by the Plioc1 seismic horizon, and a last phase active until recent times 156

157 (Figure 2c).

The compression domain in the outer shelf, in which 6 fault-related folds totalize 4 to 158 9 km of shortening, as measured from the cross-section in Figure 2c. This wide range 159 of shortening reflects uncertainties on the time to depth transformation. The structures 160 are regularly spaced, with an average separation of 10 km between each consecutive fold 161 crests. A precise timing of thrust activity has yet to be published, however several authors 162 indicate that the faults are younger toward the distal parts of the delta as they approach 163 the thrust front [Morley, 2009; Sapin *et al.*, 2009; Sapin, 2010]. This in-sequence trend is 164 observed regionally [Ingram et al., 2004; Morley, 2009; Sapin et al., 2011]. 165

Recent works described a regional shortening amount in the delta toe that exceeds the 166 amount of the shelf extension [Morley, 2003, 2009; Hesse et al., 2009; King et al., 2010; Cullen, 167 2010; Sapin et al., 2013], while upslope a compressive stress regime is computed from borehole 168 failure analysis and inferred from the common observation of inverted growth faults [Tingay] 169 et al., 2009; King et al., 2010; Morley et al., 2011]. These authors refer to Pleistocene to recent 170 plate-scale shortening across NW Borneo to explain these observations, possibly resulting from 171 crustal-scale orogenic collapse mechanisms synchronous with the gravity-driven deltaic defor-172 mations [Sapin et al., 2013; Hall, 2013]. The extent of this crustal system, as described by Sapin 173 et al. [2013], is indicated in Figure 1. This model suggests that part of the shortening recorded 174 in the delta toe comes from the crustal-scale collapse system, added to the shortening linked 175 with the collapse through additional displacements along the Setap Formation detachment or 176 through inversion of inherited crustal structures below. This component of shortening adds a 177 complexity in the Brunei margin collapse system with respect to the classical gravity-driven 178 deformation model. 179

Figure 3 proposes a schematic evolution of the gravity-driven deformations since the deposition of the LMU, based on the stratigraphic evidences displayed in Figure 2c. Two main evolution steps are identified, linked with the development of two distinct gravitational collapse systems: GCS1 during the Pliocene and GCS2 during the Pleistocene. GCS1 is characterised by a major normal fault that transfers displacements toward two thrust-related folds (Figure

3), which are formed in-sequence [Sapin et al., 2009; Sapin, 2010; Sapin et al., 2011]. This 185 system overwrites Mio-Pliocene GCSs, sealed by the LMU; in fact the easternmost fold struc-186 ture is likely inherited from this initial event, while being continuously reactivated during the 187 Pliocene [Sapin et al., 2009; Sapin, 2010; Sapin et al., 2011]. The Plioc1 horizon seals this 188 collapsing event. In the Pleistocene, the gravitational collapse system is displaced toward the 189 delta toe, as the delta shelf-break is prograding (Figure 3). GCS2 is then localised along a 190 major normal fault which accommodates more than 3 km of displacement, until recent times 191 when the deformation is focused on a frontal secondary normal fault. The GCS2 event tilts the 192 Late Pliocene GCS1 folded structures, and transfers shortening in the delta toe in which four 193 in-sequence thrust-related folds are developed. 194

This kinematic model raises questions on the deformation processes that lead to the current 195 structural geometry. First of all, one can ask if the strong fluid overpressure currently measured 196 regionally in wells existed since the Late Pliocene, and were necessary to destabilise the margin 197 despite the important deltaic sedimentation since the Miocene. Ultimately, our mechanical 198 models would help refine the simple kinematic model proposed on Figure 3, by determining 199 compatible values of fluid overpressure at each kinematic step and link all these kinematic steps 200 with a coherent sedimentation model. The analytical and numerical mechanical analysis that 201 are described in the following have been developed to investigate these questions, and especially: 202

Provide first order values of fluid overpressure and effective friction angles of sediments
 that validate the proposed kinematic steps.

Refine the kinematic model by proposing additional steps compatible with our mechanical
 analysis.

9

### <sup>207</sup> Mechanical methods

# Static stability analysis of the southern Brunei margin using the critical Coulomb wedge theory

We make use of the critical Coulomb wedge theory [Davis et al., 1983; Dahlen, 1984] developed 210 for gravitational collapses with overpressured pore fluids [Dahlen, 1984; Xiao et al., 1991; Wang 211 & Hu, 2006; Mourgues et al., 2014; Yuan et al., 2015] to estimate the effective friction coefficients 212 of the detachment  $(\mu'_d)$  and in the bulk material  $(\mu'_b)$  in the cross-section considered (Figure 2c). 213 This work is similar to those of Bilotti & Shaw [2005]; Suppe [2007]; Morley [2007]; Yuan et al. 214 [2016]; King & Morley [2017], among others, which apply the critical Coulomb wedge theory to 215 various sedimentary wedges to discuss detachment strength and fluids overpressure conditions. 216 Using the geometric parameters of the Brunei margin, deduced from the cross-section (Figure 217 2c), we explore the range of fluids overpressure conditions of the detachment and in the bulk 218 compatible with the collapse currently observed in the Brunei wedge [e.g. Sandal, 1996; Morley, 219 2003; Tingay et al., 2009; Morley et al., 2011]. 220

The introduction of fluids overpressure conditions in this static stability analysis is described in the following. We define the pore-fluid pressure p and the overpressure  $\Delta p$  (difference with the hydrostatic pressure) in a submerged wedge following Hubbert & Rubey [1959]:

$$p = g[\lambda \rho z + (\rho_f - \rho \lambda)D] \text{ and } \Delta p = \Delta \lambda \rho g(z - D)$$
 (1)

at any depth z counted positively from the sea surface. The sea bed is at depth D from the sea surface.  $g, \rho_f, \text{and } \rho$  are respectively the gravity acceleration, and the volumic masses of the water and of the fluid saturated sediments forming the wedge in  $kg.m^{-3}$ . For the static approach (section 3), we define  $\rho_f, \rho$  and g = 1000, 2380 and 9.81 respectively, and for the kinematic approach (section 4) we define  $\rho_f, \rho$  and g = 1000, 2400 and 9.81 respectively. The two scalars ( $\lambda$ ) and ( $\Delta\lambda$ ) are respectively the fluid pressure ratio and the overpressure ratio, 230 such that

$$\Delta \lambda = \lambda - \lambda_{hydro}, \text{ with } \lambda_{hydro} = \rho_f / \rho.$$
(2)

 $\lambda$  varies between  $\rho_f/\rho$  and 1, respectively in hydrostatic and lithostatic conditions, so that  $\Delta\lambda$ varies between 0 and  $1 - \rho_f/\rho$ . From this we define the effective friction coefficient  $\mu'$  and the corresponding friction angle  $\phi'$  as

$$\mu' = \mu * (1 - \lambda) / (1 - \lambda_{hydro}) \text{ and } \phi' = \arctan(\mu'), \tag{3}$$

where  $\mu$  is the friction coefficient of the material in hydrostatic conditions.

In the critical Coulomb wedge theory, and throughout the present paper, the overpressure conditions are considered uniform in the bulk of the wedge. Therefore, only two values are required to define the pore pressure :  $\Delta\lambda_b$  for the bulk material, and  $\Delta\lambda_d$  for the detachment. Making the same assumption of uniformity for the friction parameters, we use the same subscripts  $\phi_{b,d}$ ,  $\mu_{b,d}$  and  $\phi'_{b,d}$ ,  $\mu'_{b,d}$ .

# Sequential analysis of the southern Brunei margin gravitational collapse system using the SLAMTec method

The theory of limit analysis provides a mathematical framework for (1) the analysis of the onset 242 of structural events, such as a thrust or a gravitational collapse and (2) the long-term evolution 243 of these geological structures, when sequentially combined with geometrical constructions of 244 fault-related folds [see the review of Leroy & Maillot, 2016]. The kinematic approach of limit 245 analysis determines an upper bound to the values of tectonic forces by finding possible failure 246 geometries [Salençon, 1974, 2002; Maillot & Leroy, 2006; Leroy & Maillot, 2016], and requires 247 no rheology other than strength criteria (the Coulomb criterion). This upper bound depends on 248 a virtual velocity field that corresponds to the tectonic movement. Optimization is achieved by 249 selecting the scalars that parametrize this velocity fields as to minimize the upper bound and 250 obtain the least upper bound [see the review of Leroy & Maillot, 2016]. The failure mechanism 251 associated to the least upper bound is said to be dominant, as its load cannot be exceed without 252

triggering it. It has been shown that limit analysis reproduces and extends naturally the classical critical Coulomb wedge theory, while it also provides solutions for complex structural geometries and predictions for the localisation of the deformation [e.g. Cubas *et al.*, 2008; Souloumiac *et al.*, 2009; Mary *et al.*, 2013a,b; Yuan *et al.*, 2016; Leroy & Maillot, 2016].

Yuan et al. [2015] have applied the kinematic approach of limit analysis to simulate gravity-257 driven deformations, and Yuan [2016]; Yuan et al. [2016] adapted the sequential version (called 258 SLAMTec, for Sequential Limit Analysis Method for Tectonics, Mary et al. [2013a,b]) to fol-259 low gravitational collapses through time. Considering geological materials as overpressured 260 Coulomb frictional material, SLAMTec is a forward method that detects at each increment of 261 sedimentation a possible gravitational collapse (Figure 6). Optimal thrust and normal fault 262 locations (respectively, the points G and J, Figure 6) and dips are determined using the maxi-263 mum strength theorem [see Leroy & Maillot, 2016, for a full explanation]. The basin geometry 264 is then updated using geometrical rules that maintain the section volume constant, apart from 265 the sedimentation input (Figure 6). 266

In the SLAMTec routine for gravitational collapse, the stability of the wedge is first analysed using limit analysis as developed by Yuan *et al.* [2015]. Depending on the results, two cases are possible (Figure 6):

- if the wedge is unstable, it is deformed incrementally by gravitational collapse until a
 new stable state is reached. While active, the faults undergo instant friction softening,
 promoting further collapses.

- if the wedge is stable, sedimentation is implemented according to three parameters (distal
 aggradation, proximal aggradation and progradation), which create a new topographic
 surface (Figure 6).

Appealing only to Coulomb frictional parameters, SLAMTec forward solutions are only dependent on sedimentation rates and are not dependent on any rheological sensitivity to strain rates.
The modelling ends when the prescribed amount of sedimentation is reached.

In this work, SLAMTec is used to study the influence of the sedimentation and the fluid overpressure on the dynamics of the Brunei margin collapse. Assuming a constant detachment

geometry through time, we design a prototype of the Brunei margin's geometry at the time 281 of the LMU deposition from the structural interpretation of Sapin *et al.* [2009]; Sapin [2010], 282 displayed in the cross-section Figure 2c. We propose ranges of values for the sedimentation 283 parameters using the thickness of the sedimentary formation in the considered cross-section as 284 a rough guide (Figure 2c). The results of the static stability analysis are used to reduce the 285 explored parameters' space and predefine a range of effective friction coefficients compatible 286 with gravity-driven deformations in the considered prototype. Gravity-driven deformation in 287 this geological prototype is followed through time since the LMU deposition using SLAMTec 288 and for different set of parameters. Effective friction coefficients and sedimentation parameters 289 values that generate simulations matching best a set of objective geometric and kinematic 290 criteria are then estimated using an inverse approach. 291

# <sup>292</sup> Determination of the effective friction angles of the Brunei margin <sup>293</sup> sediments using the critical Coulomb wedge theory

We now apply the general formulation of the critical Coulomb wedge theory to the southern part 294 of the Brunei wedge, using mean values of topographic and detachment slope angles measured 295 on the cross-section Figure 2c. In Figure 4, critical limits are calculated using the critical 296 Coulomb wedge theory, as a function of the topographic ( $\alpha$ ) and detachment ( $\beta$ ) slopes, for 297 given bulk and detachment strengths and fluid overpressure. The entire limits are given in 298 Figure 4a for  $\phi_{b,d} = 30^{\circ}$  and  $20^{\circ}$  respectively,  $\mu_{b,d} = 0.577$  and 0.364 respectively and using 299  $\lambda_{hydro} = 0.42$ . Setting  $\Delta \lambda_b = 0.31$  and  $\Delta \lambda_d = 0.57$  in equation (3), gives  $\phi'_b = 15^\circ$  and 300  $\phi'_d = 0.4^\circ$ . The critical limits resulting from this calculation predict three states depending on 301 the wedge geometry (Figure 4a): stable sliding on the detachment in the grey zone, compressive 302 internal deformation along the dashed line (for  $\beta \leq 3.5^{\circ}$ ), or gravitational collapse along the 303 solid black line. In Figure 4b, we zoom around the region of interest (the mean  $\alpha$  and  $\beta$  values 304 measured on the cross-section (Figure 2c)), and draw the envelopes for different values of  $\phi'_d$ , 305 each distinctly coloured. Most points are located around the critical limit for gravitational 306 collapse for  $\phi_d' \approx 0.8^{\circ}$ . It highlights that the recent collapsing movements observed in the 307

Brunei margin imply very low effective friction values on the detachment, and therefore largefluid overpressure.

Figure 5 presents the critical limit in terms of  $\phi'_b$  and  $\phi'_d$  that destabilises the southern 310 Brunei margin at its current geometry, fixing  $\alpha$  and  $\beta$  at 2° and 1.8° respectively. Analysis of 311 the wedge state have been performed on 32 coupled values ranging from 10° to 20° for  $\phi'_b$ , and 312 from 0.2° to 1.4° for  $\phi'_d$ , which correspond to  $\Delta \lambda_{b,d}$  values ranging from 0.403 to 0.214 and from 313 0.574 to 0.541, respectively. In Figure 5, each analysis is represented by a cross and is coloured 314 with respect to calculated deformation state: light grey if the wedge is stable and dark grey if 315 it is collapsing. Using these results, we can draw the critical limit between margin collapse and 316 stability as function of  $\phi'_b$  and  $\phi'_d$ , which follows a linear relationship (Figure 5). This critical 317 limit seems to be almost independent from  $\phi'_b$ , as a drop in friction of almost 10° in the bulk is 318 compensated by a drop of only 1° in the detachment. As a result, independently of  $\phi'_b$  values, 319 the critical limit for gravity collapse in the Brunei margin is defined for  $\phi'_d$  values ranging from 320 0.4 to  $1.3^{\circ}$ . 321

This critical Coulomb wedge analysis highlights the overall stability of the southern Brunei 322 margin geometry, as extreme fluid overpressure are needed to induce gravitational collapse. 323 For example, assuming a value of  $\phi'_b$  of 10°,  $\Delta \lambda_d$  must be up to 0.547, which represents 94 % 324 of the lithostatic pressure at the detachment depth, to induce the collapse currently observed 325 in the margin. However, this preliminary analysis has two limitations. First, the margin 326 is represented by a perfect, infinite wedge, whereas the Brunei wedge is characterised by a 327 surface and detachment topography. Second, this analysis only concludes on the stability of 328 the margin at present-day with its current geometry. No clues are given on the localisation of 329 the deformation, the geometry of the faults and their evolution and the role of surface processes. 330

# Mechanical analysis of the Brunei margin gravitational collapse using Limit Analysis

#### **Geological prototype**

#### 334 Geometry and boundary conditions

Figure 7 sums up the boundary conditions used to model the southern Brunei margin using 335 SLAMTec. The prototype geometry is inspired from the cross-section presented in Figure 2. 336 The prototype extends over 160 km (Figure 7) from the front of the inverted province in the delta 337 plain to the frontal limit of deformations in the delta toe. Topographic and detachment slope 338 angles ( $\alpha_{1,2,3}$  and  $\beta$  respectively) have been estimated from measurements on the cross-section 339 (Figure 2c). We assumed that they are constant since the Pliocene and they are accordingly 340 constant in our simulations. The lateral boundary conditions consist of fixed, undeformable 341 walls (Figure 7). We thus neglect the regional far-field compression that impacted the structural 342 evolution of the margin during the Plio-Pleistocene, and concentrate on the GCS. 343

#### 344 Mechanical parameters

We recall that SLAMTec models are composed by only two types of materials: bulk and 345 detachment, each described by a uniform friction coefficient, a fluid overpressure, and a volumic 346 mass. We choose  $\phi_b = 30^\circ$ ,  $\phi_d = 10^\circ$  and  $\lambda_{hydro} = 0.417$  throughout the analysis, which are 347 mean values describing the sediment rheology. We then let the overpressure  $\Delta \lambda_{b,d}$  take values 348 such that, according to (2) and (3),  $\phi'_d$  ranges from 0.05° to 0.7° and  $\phi'_b$ , from 9° to 15°. During 349 their activities, normal faults and thrusts undergo friction softening which instantaneously 350 drop their friction from  $\phi_b = 30^\circ$  to  $\phi_f = 1^\circ$ , promoting further collapse at each incremental 351 step. After slipping, when a stable state is recovered, the fault retrieves its initial friction  $(\phi_b)$ 352 instantaneously. 353

In the Brunei margin the prograding coarse-grained deltaic sandstones transitioned into fine-grained pro-delta shales toward the basin [e.g. Sandal, 1996]. In addition, the top of the pro delta shales also marks the top of main fluid overpressure [Tingay *et al.*, 2009]. It potentially implies major mechanical property contrasts between the pro delta shale and the deltaic sandstone. However in the southern part of the Brunei margin, other detachment levels and disharmony only produce second-order structural features (Figure 2c), which suggest that they did not account for a large part of the shortening in this part of the margin. For that reason, we consider that simple prototypes with only two overpressured Coulomb frictional materials, the bulk and the detachment, should provide a reasonable description, i.e. not strongly biased, of the mechanical behaviour of the Brunei margin.

#### <sup>364</sup> Loading parameters: sedimentation

Because no major regional erosion events are registered in the southern part of the basin during the Plio-Pleistocene [Morley, 2003; Sapin, 2010], we neglect erosion processes, and we describe the sedimentation acquired since the LMU at the Mio-Pliocene transition, 5.33 Ma ago with three lengths (Figure 7a):

- Proximal aggradation (PA): the thickness of aggrading sediments in the delta plain,

Progradation (PROG): the horizontal displacement of the shelf-break, i.e. the point
 separating the delta plain and the delta slope,

- Distal aggradation (DA): the thickness of aggrading sediments in the delta toe.

These parameters can be roughly estimated on the cross-section in Figure 2c: 30 km of progradation, 3 km of proximal aggradation and 1.5 km of distal aggradation. However, (1) no decompaction correction have been applied, (2) consequent uncertainties exist on the time to depth conversion and the seismic interpretations and (3) local variations of the sediment thickness have also been observed over the basin [Van Rensbergen *et al.*, 1999; Morley, 2003; Sapin, 2010]. Therefore, in our parametric exploration, we consider substantial variations around these values (Table 1).

Recalling that these lengths were acquired from the LMU to the present-day time, over a period of 5.33 Ma, the corresponding sedimentation rates are given in the last three columns of Table 1. We also give the Thickness Ratio TR = DA/PA in column 9 of Table 1 for further reference. All simulations were performed using 500 incremental steps (Figure 6), each step therefore corresponding to a time step of  $5.33 \ge 10^6/499 = 10681$  years.

# Impact of the fluid overpressure and the sedimentation parameters on the evolution of the collapse within the prototype

Before proceeding to a full parametric exploration in section 5.3, we first illustrate the effects of the mechanical and sedimentation parameters with the help of six simulations (S1 to S6, Table 1).

#### <sup>390</sup> Impact of the fluid overpressure conditions

The final model geometry of S1 (Figure 8a) shows an extensional domain in the delta plain composed by several outcropping normal faults cumulating 3.9 km of slip over a region about 10 km wide. Most of the slip is accommodated through a major fault that develops a basin-ward half-graben. Six fault-related structures developed in the delta toe in response to the collapsing events. The faults (2) and (3) and the faults (4) and (5) are separated from each other by less than 2 km and we conclude that only four folds formed, each accommodating roughly the same amount of shortening and each fold's crest separated from the other by 5 to 10 km.

The evolution of the position of the normal fault/thrust fault pair is given by the successive 398 positions of the J and G points through time (Figure 6b), called a G-J gram following Mary 399 et al. [2013a]. Between 5.33 Ma (beginning of the simulation) and 1.6 Ma, sediments accu-400 mulate at the prescribed rates and the margin remains stable. Progressively, the differential 401 loading increases because PArate > DArate, until the margin collapses at 1.6 Ma (Figure 8b). 402 The margin remains strongly unstable and every second or third sedimentation step triggers 403 additional gravitational collapse. Normal fault outcrops prograde with the shelf-break, while 404 the local out-of-sequence thrusts (2) and (4) reactivate the earliest folded structures at 0.5 Ma 405 and 0 Ma respectively (Figure 8b). 406

In the next simulation (S2),  $\phi'_d$  is set to 0.15° instead of 0.25° (Table 1), reflecting an increase in the detachment overpressure. Destabilisation of the margin (Figure 9a) occurs earlier, at 3.2 Ma, and exhibits 7 km of additional slip on the extensional domain. Both extensional
and compressive zones are wider, with numerous out-of-sequence reactivations thrusting events
(Figure 9b). Note that the normal faults position again prograde with the shelf-break; in
fact this is a constant observation for any prescribed boundary conditions and mechanical
parametrisation in our models.

#### <sup>414</sup> Impact of the sedimentation parameters

Simulation S3 differs from S1 by an increased progradation of about 18% (Table 1) that stabilises 415 the margin (Figure 9b). We recall that the shelf-break progradation is performed conserving 416 the topographic angles  $\alpha_1$ ,  $\alpha_2$  and  $\alpha_3$  and with constant model length. Therefore at each 41 sedimentation step the wedge thickness in the delta slope region is increased while the delta plain 418 length is reduced. Taken together both effects (i.e. wedge thickness increase and delta plain 419 length reduction) result in the margin stabilisation [Yuan, 2016; Yuan et al., 2016]. As such, 420 when considering high values of PROGrate, the stabilisation of the margin can be considered 421 as a boundary effect since it is, at least partly, linked with the initial length of the prototype. 422 In S4, PArate is increased by ~ 40% to reach PArate = 0.66  $mm.y^{-1}$  (Table 1). The 423 resulting simulation records numerous collapsing events (Figure 9c), which cumulate 17.2 km 424 of displacements in the extensional zone. The collapse of the margin formed a thick extension 425 zone aggregating multiple prograding normal faults. The large difference between PArate and 426 DArate, highlighted by the low TR value (Table 1), puts the margin in a collapsing critical state 427 as early as 3.8 Ma. Long-term collapse during the remaining 3.8 Ma results in the formation 428 of a highly deformed compressive zone in the delta toe. 429

Simulations S5 and S6 have identical sedimentation parameters, except for DArates (with respective values DArate = 0.18  $mm.y^{-1}$  and DArate = 0.28  $mm.y^{-1}$ ), and using distinct  $\phi'_d$ values (Table 1) so that approximately 5.5 km of slip is cumulated along the normal faults of both simulations. The first observation is that, when DArate is increased by ~ 40% (in S6), the value of  $\phi'_d$  must be increased to 0.7° to reach similar cumulative slips values than in S5. Another way to tell is that more fluid overpressure are necessary in S5 to sufficiently

lower the friction on the detachment level to reach similar values of collapse than in S6. In S5, 436 the collapse of the margin starts at 2.7 Ma and formed a narrow extension zone aggregating 437 numerous normal faults. Thrusts are developed in two deformation phases: in-sequence until 438 1.6 Ma and then alternating out-of-sequence and in-sequence events until the simulation stops 439 (Figure 9d). S6 displays a similar final geometry and evolution pattern (Figure 9e), except that 440 the GCS is developed earlier and that a wider extension zone is formed. This last characteristic 441 results from an increased time interval between two collapsing events than in S5, which is caused 442 by the higher DArate value of S6. Another feature that is important to note is the propagation 443 of the shortening front, which is strongly reduced in the S6 experiment compared to the S5 444 (Figure 9c and d), which results from the higher sedimentation rate in the delta toe. 445

Note finally, that in some simulations (S2, S4, S5), the frontal thrusts seem to reach the end wall of the prototype, indicating that they would have been located further seaward, had the prototype been longer. We nevertheless keep the same prototype for the following inverse analysis. Indeed, such biased simulations are conflicting with the selection criteria, as we have verified a posteriori when analysing the inversion results.

# <sup>451</sup> Inversion of effective friction and sedimentation parameters compatible with the <sup>452</sup> observed gravitational collapses in the Brunei margin

We conclude from the previous examples that our mechanical prototype of the Brunei margin can reproduce a GCS with realistic cumulative slip and map length. We now proceed to determine all the parameter values that yield simulations matching best the following four criteria, in inclusive order (Figure 10):

- 1. The margin is initially stable and collapses during the sedimentation.
- 2. The cumulative slip on the normal faults is between 4 and 9 km; this large range results
  from uncertainties surrounding time-to-depth conversion and the structural interpretation.
- 3. The final length of the GCS (or GCSs) is equal to 100km.
- 462 4. Two distinct GCSs are formed sequentially.
  - 19

The ranges of values explored for each parameter are given in table 1, row "Param. study". Six values are selected for  $\phi'_b$ , which range from 9° to 14° with a 1° interval. Eleven values are selected for  $\phi'_d$ , which range from 0.05° to 0.7° with a 0.05° interval until  $\phi'_d = 0.4°$ and then a 0.1° interval. Three values are selected for each sedimentation parameter, which are in terms of rates: PArate = [0.47; 0.56; 0.65]  $mm.y^{-1}$ , DArate= [0.19; 0.28; 0.37]  $mm.y^{-1}$ , PROGrate=[4.7; 5.6; 6.4]  $mm.y^{-1}$ . 1782 simulations are required to treat each set of parameters thus defined.

All the simulations performed are shown in Figure 11 as crosses in  $(\phi'_d, \phi'_b)$  graphs. Each 470 graph corresponds to single values of PArate and PROGrate, and to three values of DArate. 471 Therefore, each cross represents three simulations, for DArate = 0.19, 0.28 and 0.37  $mm.y^{-1}$ . 472 Crosses located above the oblique black line yield simulations that are unstable at the initial 473 state, prior to sedimentation. They are discarded because they do not fit criterion 1. The 47 physical reason is that the effective friction angles are too low for the prototype to sustain itself 475 without collapse. The unstable domain is only dependent on the initial prototype geometry 476 and the values of  $\phi'_d$  and  $\phi'_b$ . Therefore the black line is identically located in each graph of 477 Figure 11. Conversely, crosses below a coloured solid line are simulations that remain stable 478 throughout the sedimentation and are discarded by criterion 1, because in those cases, the 479 effective friction angles are too high for the margin to collapse, even when loaded by the to-480 tal prescribed sedimentation. Criterion 1 is verified by simulations that have crosses located 481 between the black line and the orange line (for DArate = 0.37  $mm.y^{-1}$ ), or purple line (for 482 DArate = 0.28  $mm.y^{-1}$ ), or blue line (DArate = 0.19  $mm.y^{-1}$ ): these simulations are initially 483 stable and do collapse before the total prescribed amount of sedimentation is applied. For 484 example, the set of parameters of S1 places the simulation in the collapse domain for DArate 485  $= 0.19 \ mm.y^{-1}$  (Figure 11a), implying the development of margin collapse during the sedimen-486 tation as observed in Figure 8. The same experiment but with DArate = 0.28  $mm.y^{-1}$  (i.e. 487 looking at the purple solid line) places the simulation in the stable domain (Figure 11a). These 488 results show that even lower values of  $\phi'_d$  and  $\phi'_b$  than in the critical Coulomb wedge prototype 489 (Figure 5) are necessary to trigger an instability. This is due to the stabilising role of the delta 490

toe which does not exist in the critical Coulomb wedge prototype [Yuan et al., 2016].

- The following trends for the sedimentation parameters appear from the comparison of the graphs in Figure 11:
- Increasing PArate moves in parallel the solid coloured lines to the right part of the graphs, that is the higher  $\phi'_b$  and  $\phi'_d$  regions. It means that more couples of  $\phi'_b$  and  $\phi'_d$  comprised in our search respect the criterion 1 when PArate is increased. For example, referring to DArate = 0.19  $mm.y^{-1}$  (i.e. the blue solid line) in Figure 11b, the margin is stable for  $\phi'_d$  and  $\phi'_b$  fixed to 0.6° and 10° but it becomes unstable when PArate  $\geq 0.56 \ mm.y^{-1}$ (Figure 11b, c).
- Increasing DArate moves the solid coloured lines to the left part of the graphs, that is the lower  $\phi'_b$  and  $\phi'_d$  regions. It means that less couples of values  $(\phi'_b, \phi'_d)$  comprised in our search respect the criterion 1 when DArate is increased. For example, in Figure 11a, fixing  $\phi'_d$  and  $\phi'_b$  at 0.25° and 11° respectively, the margin collapses for DArate = 0.19  $mm.y^{-1}$  while it remains stable for DArate = 0.28  $mm.y^{-1}$ .
- <sup>505</sup> Increasing the PROGrate moves the solid coloured lines to the left part of the graphs, <sup>506</sup> that is the lower  $\phi'_b$  and  $\phi'_d$  regions. Therefore PROGrate and DArate co-vary, even if <sup>507</sup> PROGrate variation has less impact on the margin collapse.

Simulations represented by crosses located closer to the black "unstable initial state" line are 508 characterized by the most cumulative slip, while these displacements decrease as crosses move 509 closer to the corresponding coloured "collapse/stable limit" solid line. At the collapse/stable 510 limit, simulations only display one gravitational collapse event, which results in 100 to 500 m 511 of cumulative slip depending on the DArate value. The decrease follows a linear trend, which 512 makes the cumulative slip values predictable. The explanation is that, with constant sedimen-513 tation parameters, increasing  $\phi'_b$  and  $\phi'_d$  postpones proportionally the triggering of the margin 514 instability. From the moment that the critical state is achieved, gravitational collapse occurs 515 at almost every sedimentation step. Therefore cumulative slip is greater when collapse happens 516 earlier, and as such when  $\phi'_b$  and  $\phi'_d$  are lower. 517

An important lesson highlighted by the Figure 11 is that, independently from  $\phi'_{b}$  and  $\phi'_{d}$ 518 values, the cumulative slip computed in our simulations are dependent on the relative values of 519 DArate and PArate, expressed by the TR value. As TR increases, meaning as DArate increases 520 compared to PArate, the critical limit for gravity collapse moves towards lower  $\phi'$  domains (see, 521 for example, the respective positions of the coloured solid lines in Figure 11a, b, c with respect 522 to their TR values), which indicates that higher fluid overpressure are necessary to create the 523 conditions for gravitational instabilities. This was also described in the comparison between 524 the S5 and S6 experiments. 525

The simulations that fit the criterion 2 are shown as coloured bands delimited by dashed 526 lines in Figure 11. The inferior limit of the bands, that is the one closer to the solid coloured 527 line, corresponds to simulations displaying 4 km of cumulative slip, while the superior limit (the 528 one closer to the solid black lines) corresponds to simulations displaying 9 km of cumulative 529 slip. The evolution of the cumulative slip between these too values limiting our search is linear. 530 The band envelopes isolate a total of 86 simulations where the cumulative slip is comprised 531 between 4 and 9 km. It should be noted that the envelopes shrink with increasing TR (see for 532 example the different envelopes in Figure 11f). Because cumulative slip is close to zero at the 533 solid coloured lines and maximum at the solid black lines, and because with increasing TR the 534 solid coloured lines are moved closer to the solid black lines, for higher TR values the linear 535 coefficients of the cumulative slip vs  $\phi'$  values relationships is increased. It means that at each 536 increment of  $\phi'$  the cumulative slip is increased further when TR is higher. The result is that 537 with higher TR values the range of experiments that respect the criterion 2 is reduced, until 538 becoming virtually close to zero, as seen for instance when TR=0.67 in Figure 11b. 539

Simulations fitting the criterion 3 are shown as bold crosses. Only 14 simulations are characterised by a final GCS length smaller than 105 km. S6 (Figure 9e) is an example of one of these (Figure 11b). Simulations that respect criterion 3 have systematically a TR value superior to 0.5 (Figure 11); high values of DArate compared to PArate are indeed needed to limit the propagation of the deformation to 100km, as explained comparing S5 and S6 (Figure 9d, e).

The 14 remaining simulations define the most realistic set of parameters. The range of 546 values for these successful simulations is determined as follows:  $\phi'_d = [0.1 - 0.5]^\circ$ ,  $\phi'_b = [9 - 12]^\circ$ 547 and a TR value superior to 0.5. In Figure 12, the final geometry of one of these best-fit examples 548 (S7 in Figure 11e, with DArate =  $0.28 \ mm.y^{-1}$ ) is compared with the geological cross-section. 549 The sedimentation progressively builds up the margin until it reaches a critical point marking 550 the start of its gravitational collapse (Figure 12a). The first steps of these collapse events are 551 characterized by the formation of 5 in-sequence thrusts, that define 5 folds. Starting at 1.9 Ma, 552 out-of-sequence thrusts reactivate previous fold structures as newly formed fold deformed the 553 most distal regions. At the final stage of sedimentation, the collapse becomes progressively 554 focused on a single normal fault creating an important depocenter (Figure 12c). Deformation 555 in the compressive region is diffuse, characterised by seven consecutive fold structures formed 556 by eleven thrusts spread over 30 km. The position and size of the extension and compression 557 regions are similar in both the simulation and the geological cross-section 558

<sup>559</sup> Criterion 4 was missed by all the simulations. One GCS formed if any, because sedimentation <sup>560</sup> rates and effective frictions were kept constant in each simulation. We show in the next section <sup>561</sup> that a single change in the basal effective friction can produce a temporary arrest of the current <sup>562</sup> GCS, followed by a new GCS frontward.

#### <sup>563</sup> Improved parametrisation of the Brunei margin

As seen above, even in our best simulations, the subsidence in the delta plain is spatially 564 distributed instead of forming two GCS's with distinct blocks separated by normal faults. 565 To remedy this discrepancy we let the detachment effective friction angle increase during the 566 sedimentation. S8 is identical to S7, except that the value of  $\phi'_d$  starts at  $\phi'_d = 0.25^{\circ}$ . In Figure 567 11e, it corresponds to the starting point of the simulation defined by  $\phi'_d = 0.25^\circ$ ,  $\phi'_b = 10^\circ$  and 568  $DArate = 0.28 mm.y^{-1}$ . A GCS forms after one sedimentation step (Figure 13, blue lines and 569 crosses) and it is stopped by increasing  $\phi'_d$  to 0.35° at 4.4 Ma. Sedimentation then continues, 570 the delta progrades without collapse nor internal deformation and seals GCS1 until the Plioc1 57 deposits (Figure 13b). This stable phase displaces the shelf break toward the delta toe until, at 572

2.7 Ma, the margin becomes unstable again and creates a second GCS in front of the first one
(Figure 13b, red lines and crosses). As a result, the final geometry of the cross-section is better
simulated, as criterion 4, i.e. the occurrence of two distinct GCS's is now verified (Figure 13c).
Note that the total cumulative slip on the normal faults comprising the two successive GCSs
is 5 km, which still satisfies the second criteria.

Other models could be designed to respect the fourth criterion. For example by letting the sedimentation parameters vary rather than the friction properties. The selection between sedimentation or fluid overpressure variations must be made in accordance with geological information that is still lacking.

### <sup>582</sup> Redrawing the Plio-Pleistocene kinematics

Overall the modelling results validate mechanically the kinematic evolution presented in Figure 583 3, because they can reproduce the occurrence, slip magnitude, and total length of the GCS 584 (criteria 1, 2, 3) using mechanical and sedimentation parametric ranges compatible with the 585 present-day geological observations. The ranges of the effective friction angles are  $9^{\circ} \le \phi'_b \le 12^{\circ}$ 586 and  $0.1^{\circ} \leq \phi'_d \leq 0.5^{\circ}$ . Using equations (1), (2) and (3) and Table 1, these give pore pressure 587 values between 59 and 62 MPa along the detachment in the thrusting region of the delta toe. 588 These values can be compared to pressure data available in Tingay [2003] for three neighbouring 589 wells in the thrusting region (Ketambak 1, Z1-1 and Parak-1), among which are repeated 590 formation tester data, the static mudweigth, leak off pressures and fracture closure pressures. 591 These data highlight a significant fluid overpressure window drilled from 2500 m to 3000 m 592 below the sea surface, which corresponds to the top of the pro-delta shales. It gives a maximum 593 pressure gradient estimated between 16 MPa/km and 18 MPa/km, which is in accordance with 594 the 19 MPa/km to 20 MPa/km gradients found at deeper levels in our models. 595

Figure 11 could in the same manner be transferred into pore-pressure maps at any depth and any geological time defining the minimum pore pressure needed for the geological system to collapse, and jointly the maximum pore pressure for the geological system to remain stable. These quantities provide useful guidelines to validate basin modelling results where pore-pressure is calculated using prescribed structural geometries [e.g. Neumaier *et al.*, 2014; Burgreen-Chan
 *et al.*, 2016], as they provide the end-member pore-pressure values beyond which the prescribed
 kinematics become mechanically unrealistic.

Our modelling approach failed to produce two distinct GCSs (criterion 4), and this suggests the occurrence of an external event during the margin evolution, that was not accounted for in our modelling since we used constant parametric values throughout the simulations. We propose two hypotheses validated by the SLAMTec approach for this event :

- Variations of accomodation space in the basin during the Pliocene, which manifest itself
   as variations in the PArate and PROGrate. This model refers to external factors, most
   likely linked with the slab break-off and crustal rebound in Borneo during the Pliocene.
- Decrease in the fluid overpressure state within the post-Miocene sediments, consequently
   to a major fluid discharge event. This model refers to internal factors, linked with dynamic
   variations of the Setap Shales permeability, most likely a consequence of the lithostatic
   fluid overpressure in the sedimentary formation lasting from the Neogene to Recent time.

Note that other processes can be considered to explain these shifts in depocentres (that are 614 common features of delta systems), such as: (1) growth fault strain hardening due to depletion 615 of the weak layer (i.e. a weld develops), or (2) overpressure is locally depleted from beneath 616 the depocentre, or (3) sedimentation rates are such that a single faults cannot displace fast 617 enough to accommodate all the sediments and another depocentre develops simultaneously. 618 Since SLAMTec current implementation does not have these mechanisms properly built into it, 619 it de facto excluded them from our hypotheses. That said, it does not exclude the validity of the 620 two models proposed above, but reinforce the fact that they must be considered as end-member 621 structural solutions. 622

We now redraw the schematic geological scenario presented in Figure 3 taking into account the inversion results in terms of fluid overpressure and sedimentation patterns, inspired by each end-member hypothesis proposed for the development of the two subsequent GCSs (Figure 14). In the first end-member model (Figure 14a), the fluid overpressure gradient is fixed so that  $\phi'_d = 0.25^\circ$  and  $\phi'_b = 10^\circ$ . We make the assumption that the distal aggradation is constant as well

as the sediment fluxes. After the LMU deposit, the delta is characterized by a prograding delta 628 sequence, which is conjugated with low aggradation rate in the delta plain (Figure 14a). Results 629 of the inversion available in Figure 11 confirm the stability of the margin for such sedimentation 630 model and fluid overpressure values. This sequence is followed by an important aggradation 631 phase, lasting until the Late Pliocene, which tends to destabilise the margin. According to 632 the inversion table (Figure 11), it leads to the formation of the first GCS, creating two large 633 thrust-related folds which are formed simultaneously. During the Late Pliocene, the delta 634 is again marked by an important progradation phase, which leads to a second stabilisation 635 period that contributes to greatly move the shelf break toward the delta front. The Pleistocene 636 period marks a second phase of delta aggradation, which contributes to form the second GCS. 637 Four thrust-related folds are formed principally in-sequence, with occasionally out-of-sequence 638 reactivations. 639

The second end-member proposition (Figure 14b) is a direct transcription of the model 640 results shown in Figure 13. The deltaic growth is assumed to be regular during the Plio-641 Pleistocene, while being particularly important due to the rapid uplift of Borneo since the 642 slab break-off in the early Pliocene. The high fluid overpressure in the detachment layer, 643 consecutive of the deposit of large volumes of sediment on top of the low permeability Setap 644 shales since the Miocene, is responsible for the formation of the early GCS. The reduction 645 of fluid overpressure gradients within the detachment layers would then stabilise the margin 646 until the Late Pliocene. While counter-intuitive, fluid overpressure drops could indicate the 647 fracturation of the shales layers, leading to fluids discharge and the regional increase in the 648 seal permeability. The continued sedimentation of the delta would then progressively drive the 649 margin back to gravitational instability, leading to the formation of the second GCS during the 650 end of the Pliocene and the Pleistocene-Recent times. 651

The two end-member kinematic scenarios (Figure 14) still need important back-up from a refined geologic study of the area to be validated. The set-up, mechanics and loading parameters we applied in our models are sensibly simplified from regional geology, and therefore the implementation of additional controlling parameters in SLAMTec (such as a more com-

plex sedimentation model, inherited faulted structures, detachment dips variations in space 656 and time and/or basement subsidence) could lead to supplementary models for the sequential 657 development of the GCSs. Still, the two proposed scenarii can be used as guidelines to de-658 fine the missing data needed to propose refined structural kinematic solutions of the southern 659 Brunei margin; notably the sequence stratigraphic framework of the Plio-Pleistocene in the 660 cross-section area (i.e. the migration of the sedimentary system) and the search for clues help-661 ing to describe the fluids flows in the fractured state and cements of the Setap shales and the 662 above stratigraphy (as in Gasparrini et al. [2014]; Beaudoin et al. [2014] for instance). 663

## 664 Conclusion

We consider the development of large scale Gravitational Collapse Systems (GCS) offshore 665 NW Brunei that are resulting from massive sediment influxes of the large post-mid-Miocene 666 Baram and Champion deltas. Since the Pliocene (5.33 Ma), due to the differential sediment 667 loading between the delta plain and the seaward deep basin, many large normal faults formed 668 in the plain ground. The consecutive seaward displacement occured down to the Setap shale 669 formation (Lower Miocene) acting as the major detachment level transferring extension in the 670 plain into a compressive fold-and-thrust belt at the delta toe. Overall, the GCSs are more than 671 a hundred km wide in cross-section, with 4 to 9 km of cumulative slip on the normal faults. 672

Our aim is to validate and refine this scenario with the help of mechanical concepts (equilibrium, Coulomb criterion and a part of Limit Analysis called the maximum strength theorem), and to thus constrain the compatible mechanical parameter ranges.

The present day cross-section exhibits a low taper between the surface topography and the detachment that implies, according to the critical Coulomb wedge theory, a low effective friction angle in the bulk ( $10^{\circ}$  to  $20^{\circ}$ ) and a very low one in the detachment ( $0.2^{\circ}$  to  $1.8^{\circ}$ ), assuming that the GCS are currently in a critical state of activation.

Next, we use the maximum strength theorem with the SLAMTec software that allows us to simulate the evolution of the GCSs since the Pliocene using only a few parameters: sedimentation rates, bulk and detachment friction angles, and pore pressure profiles. The numerical

efficiency of this semi-analytic method allows us to explore the parametric space with nearly 683 2000 simulations and to determine the parameter ranges that reproduce the occurrence of GCS, 684 their total cross-section width, and the cumulative slip on the normal faults. In doing so, we 685 found a narrower range of effective friction angles: from  $9^{\circ}$  to  $12^{\circ}$  in the bulk and from  $0.1^{\circ}$  to 686  $0.5^{\circ}$  in the detachment. The high fluid overpressures explaining these low effective strengths 687 should have been occurring since at least the LMU deposits during the Pliocene to respect the 688 present-day structural observations. However, no simulation reproduced the formation of the 689 two prograding sequences of GCS observed in the seismic data. This discrepancy points to 690 a major change in either one of the main controlling factors of the collapse: the sedimentary 691 migration of the delta, or changes in the pore pressure magnitudes. Based on this, we propose 692 two qualitative structural scenarii, with estimations of the variations in sedimentation rates 693 or in pore overpressures that could be responsible for the change of active GCS during the 694 Pliocene. 695

These mechanical analyses confirm the overall kinematic evolution of the cross-section, 696 demonstrating its mechanical feasibility for parameter values that fall within the range of the 697 geological observations. They illustrate how mechanical modelling can be used in a practical 698 way to help design a cross-section with an appropriate structural style and kinematics based 699 on mechanical solutions. As in the work of Caër et al. [2015], we show that it is important to 700 account for the topography and the frictional resistance of overpressured sediments or, in other 701 words, to account for the material weight and finite strength when designing a cross-section. 702 Such modelling exercises are useful to prepare the ground for more advanced thermo-fluid 703 structural scenarii, as proposed in the works of Neumaier et al. [2014]; Faille et al. [2014]; 704 Thibaut et al. [2014]; Burgreen-Chan et al. [2016]; Obradors-Prats et al. [2017]. 705

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Figure 1: NW Borneo tectonic map [modified from Sapin *et al.* [2013]; Pubellier *et al.* [2017]]. The light brown represents the crustal-scale collapse zone described by Sapin *et al.* [2013], and in the yellow region is observed the deltaic gravity-driven deformations of the Champion and Baram basin. The studied area (black frame) is centered in the offshore Brunei (see Figure 2a for details)



Figure 2: Cenozoic stratigraphy and interpreted seismic section of the southern part of the Brunei margin. a) Tectonic map of the Baram-Champion Delta and position of the selected cross-section. b) Brunei lithostratigraphy [modified from Pubellier *et al.* [2017]] and interpreted mechanical stratigraphy. c) Depth-converted interpreted seismic section of the southern Brunei margin (modified from Sapin *et al.* [2009]). Coloured lines correspond to three well-observed seismic horizons named here Mioc1, LMU and Plioc1



Figure 3: Schematic geological evolution of the deformation of the southern part of the Brunei margin from the Pliocene to present-day time. Two gravitational collapse system (GCS) are successively emplaced since the Late Pliocene.



Figure 4: The critical wedge theory applied on the present-day cross section. a) The critical limit in compression (dashed line) and gravitational collapse (full line) is displayed as function of the topographic slope  $\alpha$  and the detachment dip  $\beta$ , for friction angles of  $\phi_{b,d} = 30, 20^{\circ}$  respectively, a hydrostatic fluid pressure ratio  $\lambda_{hydro} = 0.42$  and an overpressure ratio  $\Delta\lambda_{b,d} = 0.31, 0.57$ respectively. In (b) a zoom with envelopes for various values of effective detachment friction angles  $\phi'_d$  (purple:  $\phi'_d = 0.01^{\circ}$ ; green: 0.1°; blue: 0.4°; yellow: 0.8° and red: 1°. The mean value of  $\alpha$  (2°) and  $\beta$  (1.8°) measured from the cross-section in Figure 10c is represented by a cross, surrounded by 0.5° standard deviation.



Figure 5: Critical limit between the gravitational collapse domain and the stable wedge domain in the effective friction angle for the bulk and detachment space  $(\phi'_b, \phi'_d)$ , calculated for a topographic slope  $\alpha = 2^\circ$ , a detachment slope  $\beta = 1.8^\circ$ , a detachment friction angle  $\phi_d = 10^\circ$ , a bulk friction angle  $\phi_b = 20^\circ$  and a hydrostatic fluid pressure ratio  $\lambda_{hydro} = 0.42$ . Black crosses represent a tested set of parameters in which gravitational collapse is predicted, whereas grey crosses represent a tested set of parameters in which the wedge remains stable. Both domains are separated by a linear limit strongly dependent on  $\phi'_d$ .



Figure 6: The SLAMTec algorithm. If the wedge is stable (according to Limit Analysis), an increment of sedimentation is applied according to the three parameters (progradation and aggradation). If gravitational collapse is detected, optimal thrust and normal fault (represented by the points H, I, J and F, E G) are determined using the maximum strength theorem, and an increment of slip is applied to modify the margin geometry, maintaining bulk volume constant.



Figure 7: Geometry of the prototype used for the calculation (not to scale) and values of the mechanical parameters that remain constant throughout the study (bulk friction angles  $\phi_b$ , detachment friction angle  $\phi_d$  and effective fault friction  $\phi'_f$ ). The displacement vectors of the topographic surface associated with each sedimentation parameter are also displayed.



Figure 8: Simulation S1. a) Final geometry of the prototype (in 1:1). Grey lines correspond to pre-LMU terrains, and light brown lines correspond to sedimentation during the simulation. Six faults occured in the compressive region, forming four distinct folds. b) Position of the points G and J through time (Figure 6) in red and black respectively. Thrusts position during sedimentation determines an overall in-sequence trend of fold development, with some out-of-sequence re-activations.



Figure 9: Final geometry and evolution of the G and J points (respectively the position of the thrust and the normal fault on the detachment, see Figure 6) in the simulations S2 (a) to S6 (e) (in 1:1). In the G-J grams displaying the evolution of the G-J points position with the sedimentation, black crosses correspond to J points and green crosses correspond to G points. PArate is the proximal aggradation rate, DArate the distal aggradation rate, PROG the progradation rate,  $\phi'_d$  the detachment effective friction angle and  $\phi'_b$  the bulk effective friction angle.



Figure 10: Scaled structural cross-section illustrating the criteria used to compare the simulations with the geological observations. They are, in inclusive order: (1) the collapse of the margin, (2) the cumulative extensional slip on the normal faults, (3) the length of the deformed system and (4) the existence of two distinct gravitational collapse system (GCS). The LMU limit is represented by a purple horizon.



Figure 11: Results of the parameter selection. Crosses located between the black solid line and a coloured solid line yield simulations that obey the first criterion. Blue, purple and orange lines represent respectively the results for the distal aggradation rates DArate = 0.19, 0.28 and 0.37  $mm.y^{-1}$ . Crosses within the coloured ranges delimited by dashed lines fit the criterions 1 and 2. Bold crosses fit criteria 1, 2 and 3. No simulations fits the criterion 4. Values of the four other parameters are indicated on the axes, so that all results are represented in nine graphs a), b) c), d), e), f), g), h) and i). The value of the thickness ratio TR is displayed for each set of sedimentation parameters below the DArate coloured lines. The position of the simulations S1 to S7 on the graphs are also framed. PArate is the proximal aggradation rate, PROGrate the progradation rate.



Figure 12: Geometry (in 1:1) of the simulation S7 and evolution of the G-J points position on the detachment in this simulation, defined as one of 14 simulations that match the best the cross-section. The geological cross-section is displayed above for comparison. In a), the simulated cross-section is shown at 3.4 Ma., at the starting point of the collapse. In b), crosssection at 1.6 Ma, during the out-of-sequence thrusting deformation style. In c), the final step of sedimentation. Faults with displacement vectors indicate that active faulting occurred at the displayed time-step. Dashed black lines indicate the position of the first normal fault. In the G-J gram to the right, displaying the evolution G-J points position, recall that black crosses and red crosses correspond to the roots of the normal faults and thrusts on the detachment, respectively. PA is the amount of proximal aggradation at a given sedimentation step, DA the amount of distal aggradation at a given sedimentation step and PROG the amount of progradation at a given sedimentation step.



Figure 13: Geometry of the simulation S8, and evolution of the G-J points position on the detachment in this simulation, designed to reproduce two distinct gravitational collapse systems (GCS). The geological cross-section is displayed above for comparison. In a), the simulated cross-section at 3.2 Ma, after sealing of the GCS1 (in blue). In b), the cross-section at 2 Ma, during the collapse of GCS2 (in red). In c), the cross-section at the end of the simulation. In the G-J gram, displaying the evolution G-J points position, light blue and dark blue crosses correspond to GCS1 normal faults and thrusts position on the detachment, while light red and dark red crosses correspond to GCS2 normal faults and thrusts positions on the detachment. PA is the amount of proximal aggradation at a given sedimentation step, DA the amount of distal aggradation at a given sedimentation step, PROG the amount of progradation at a given sedimentation step.



 $\Phi' d= 0.35^{\circ}; \Phi' b= 10^{\circ}$ 

Figure 14: End-member schematic geological evolution of the deformation of the southern part of the Brunei margin from the Pliocene to recent time, including the sedimentation and effective frictions values necessary to mechanically validate the section evolution. In red and green is shown the active gravitational collapse system (GCS). a) Evolution of the margin assuming a constant fluid overpressure. Major changes in the progradation and aggradation of the Baram delta lead to alternating stability and collapse periods. In recent times, the progradation of the deformation in the second GCS is represented by green and red lines. b) Evolution of the margin assuming a constant sedimentation pattern, inspired from S8. A drop in the detachment fluid overpressure stabilises the margin until the differential sediment supply (the thickness ratio TR < 1) destabilises it again, forming the second GCS.  $\phi'_d$  is the detachment effective friction angle,  $\phi'_b$  the bulk effective friction angle, "prog" the amount progradation at a given time-step and "aggr." the amount of aggradation at a given time-step.

Sim	$\Delta \lambda_d$	$\phi'_d(\phi_d = 10^\circ)$	$\Delta \lambda_b$	$\phi_b'$	$\mathbf{PA}$	DA	PROG	TR DA/B	PArate	DArate	PROGrate
NDF.	-	10 )	-	$(\varphi_b = 50)$	km	km	km	=DA/ P _	$mm.y^{-1}$	$mm.y^{-1}$	$mm.y^{-1}$
S1	0.567	0.25	0.367	12	2.5	1	25	0.4	0.47	0.19	4.7
S2	0.571	0.15	0.367	12	2.5	1	25	0.4	0.47	0.19	4.7
S3	0.567	0.25	0.367	12	2.5	1	35	0.4	0.47	0.19	6.5
S4	0.567	0.25	0.367	12	3.5	1	25	0.28	0.66	0.19	4.7
S5	0.551	0.7	0.420	9	3	1	25	0.33	0.56	0.19	4.7
S6	0.540	0.5	0.420	9	3	1.5	25	0.5	0.56	0.28	4.7
Param. study	0.577 - 0.540	0.05-0.7	0.310- 0.420	9-15	$2.5,\ 3,\ 3.5$	$1, \\ 1.5, \\ 2$	$25, \\ 30, \\ 35$	•	$0.47, \\ 0.56, \\ 0.65$	$0.19, \\ 0.28, \\ 0.37$	4.7, 5.6, 6.4
$\mathbf{S7}$	0.560	0.35	0.403	10	3	1.5	30	0.5	0.56	0.28	5.6
S8	0.566 then 0.560	0.25 then 0.35	0.403	10	3	1.5	30	0.5	0.56	0.28	5.6

Table 1: Mechanical and sedimentation parameters used in SLAMTec simulations.  $\Delta \lambda_d$  is the detachment overpressure ratio,  $\phi'_d$  the detachment effective friction angle,  $\phi_d$  the detachment friction angle,  $\Delta \lambda_b$  the bulk overpressure ratio,  $\phi'_b$  the bulk effective friction angle,  $\phi_b$  the bulk friction angle, PA the total amount of proximal aggradation in the simulation, DA the total amount of distal aggradation in the simulation, PROG the total amount of progradation in the simulation, TR the thickness ratio of the simulation, PArate the rate of proximal aggradation in  $mm.y^{-1}$ , DArate the rate of distal aggradation in  $mm.y^{-1}$ .