



HAL
open science

Benchmarking analogue models of brittle thrust wedges

Guido Schreurs, Susanne J.H. Buitter, Jennifer Boutelier, Caroline Burburry, Jean-Paul Callot, Cristian CavoZZi, Mariano Cerca, Jian-Hong Chen, Ernesto Cristallini, Alexander Cruden, et al.

► **To cite this version:**

Guido Schreurs, Susanne J.H. Buitter, Jennifer Boutelier, Caroline Burburry, Jean-Paul Callot, et al.. Benchmarking analogue models of brittle thrust wedges. *Journal of Structural Geology*, 2016, 92, pp.116-139. 10.1016/j.jsg.2016.03.005 . hal-01449311

HAL Id: hal-01449311

<https://hal.science/hal-01449311v1>

Submitted on 7 Jan 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Benchmarking analogue models of brittle thrust wedges

Schreurs Guido ^{1,*}, Buitter Susanne J. H. ^{2,3}, Boutelier Jennifer ⁴, Burberry Caroline ^{5,24},
 Callot Jean-Paul ^{6,25}, CavoZZi Cristian ⁷, Cerca Mariano ⁸, Chen Jian-Hong ⁹, Cristallini Ernesto ¹⁰,
 Cruden Alexander R. ^{11,26}, Cruz Leonardo ¹², Daniel Jean-Marc ^{6,32}, Da Poian Gabriela ^{10,27},
 Garcia Victor H. ^{10,27}, Gomes Caroline J. S. ¹³, Grall Celine ^{6,28}, Guillot Yannick ¹⁴, Guzman Cecilia ¹⁰,
 Hidayah Triyani Nur ¹⁵, Hilley George ¹⁶, Klinkmuller Matthias ¹, Koyi Hemin A. ⁵, Lu Chia-Yu ¹⁷,
 Maillot Bertrand ¹⁸, Meriaux Catherine ²⁹, Nilfouroushan Faramarz ³⁰, Pan Chang-Chih ⁹, Pillot Daniel ⁶,
 Portillo Rodrigo ⁸, Rosenau Matthias ²⁰, Schellart Wouter P. ¹⁹, Schlische Roy W. ¹⁵, Take Andy ²¹,
 Vendeville Bruno ²², Vergnaud Marine ⁶, Vettori Matteo ^{7,31}, Wang Shih-Hsien ⁹, Withjack Martha O. ¹⁵,
 Yagupsky Daniel ¹⁰, Yamada Yasuhiro ²³

¹ Univ Bern, Inst Geol Sci, Baltzerstr 1 & 3, CH-3012 Bern, Switzerland.

² Geol Survey Norway, Geodynam Team, N-7491 Trondheim, Norway.

³ Univ Oslo, Ctr Earth Evolut & Dynam, POB 1048, N-0316 Oslo, Norway.

⁴ Univ Toronto, Dept Geol, 22 Russell St, Toronto, ON M5S 3B1, Canada.

⁵ Uppsala Univ, Dept Earth Sci, Hans Ramberg Tecton Lab, S-75326 Uppsala, Sweden.

⁶ IFP Energies Nouvelles, 1 & 4 Ave Bois Preau, F-92500 Rueil Malmaison, France.

⁷ Univ Parma, Dept Phys & Earth Sci Macedonio Melloni, NEXT Nat & Expt Tecton Res Grp, Via G Usberti 157-A, I-43100 Parma, Italy.

⁸ Univ Nacl Autonoma Mexico, Ctr Geociencias, Blvd Juriquilla 3001, Juriquilla 76230, Queretaro, Mexico.

⁹ Natl Taiwan Univ, Dept Geosci, 1 Roosevelt Rd Sect 4, Taipei 106, Taiwan.

¹⁰ Univ Buenos Aires, Dept Ciencias Geol, Pabellon 2, Ciudad Univ, C1428EHA, Buenos Aires, DF, Argentina.

¹¹ Univ Toronto, Dept Geol, 22 Russell St, Toronto, ON M5S 3B1, Canada.

¹² Stanford Univ, Dept Geol & Environm Sci, Braun Hall 215, Stanford, CA 94305 USA.

¹³ Univ Fed Ouro Preto, Dept Geol, Morro Cruzeiro S-N 35, BR-400000 Ouro Preto, MG, Brazil.

¹⁴ Univ Lille Nord France, Lab Geosyst, FRE CNRS 3298, F-59655 Villeneuve Dascq, France.

¹⁵ Rutgers State Univ, Dept Earth & Planetary Sci, 610 Taylor Rd, Piscataway, NJ 08854 USA.

¹⁶ Stanford Univ, Dept Geol & Environm Sci, Braun Hall 233, Stanford, CA 94305 USA.

¹⁷ Natl Taiwan Univ, Dept Geosci, 1 Roosevelt Rd, Taipei 106, Taiwan.

¹⁸ Univ Cergy Pontoise, Lab Geosci & Environm Cergy, 5 Mail Gay Lussac, F-95031 Neuville Sur Oise, Cergy Pontoise, France.

¹⁹ Monash Univ, Sch Earth Atmosphere & Environm, Melbourne, Vic 3800, Australia.

²⁰ Helmholtz Ctr Potsdam, GFZ German Res Ctr Geosci, D-14473 Potsdam, Germany.

²¹ Queens Univ, Dept Civil Engn, Kingston, ON K7L 3N6, Canada.

²² Univ Lille, UMR 8187, LOG, F-59000 Lille, France.

²³ Kyoto Univ, Dept Civil & Earth Resources Engn, Kyoto 6158540, Japan.

²⁴ Univ Nebraska Lincoln, Dept Earth & Atmospher Sci, 214 Bessey Hall, POB 880340, Lincoln, NE 68588 USA.

²⁵ Univ Pau & Pays Adour, Lab Fluides Complexes & Leurs Reservoirs, UMR5150, BP 1155, F-64012 Pau, France.

²⁶ Monash Univ, Sch Earth Atmosphere & Environm, Melbourne, Vic 3800, Australia.

²⁷ Univ Nacl Rio Negro, Inst Invest Paleobiol & Geol, Isidro Lobo 516, RA-8332 Gen Roca, Rio Negro, Argentina.

²⁸ Columbia Univ, Marine Geol & Geophys, Lamont Doherty Earth Observ, Palisades, NY 10964 USA.

²⁹ Univ Lisbon, Dept Engr Geog Geofis & Energia, P-1749016 Lisbon, Portugal.

³⁰ Univ Gavle, Dept Ind Dev IT & Land Management, Gavle, Sweden.

³¹ E FEM Srl, CAE Struct Anal & Composite Design, CTO Area, Parma, Italy.

³² IFREMER, Dept Phys Resources & Deep Sea Ecosyst PDG REM, Ctr Bretagne, ZI Pointe Diable, CS 10070, F-29280 Plouzane, France.

* Corresponding author : Guido Schreurs, email address : schreurs@geo.unibe.ch

Abstract :

We performed a quantitative comparison of brittle thrust wedge experiments to evaluate the variability among analogue models and to appraise the reproducibility and limits of model interpretation. Fifteen analogue modeling laboratories participated in this benchmark initiative. Each laboratory received a shipment of the same type of quartz and corundum sand and all laboratories adhered to a stringent model building protocol and used the same type of foil to cover base and sidewalls of the sandbox. Sieve structure, sifting height, filling rate, and details on off-scraping of excess sand followed prescribed procedures.

Our analogue benchmark shows that even for simple plane-strain experiments with prescribed stringent model construction techniques, quantitative model results show variability, most notably for surface slope, thrust spacing and number of forward and backthrusts. One of the sources of the variability in model results is related to slight variations in how sand is deposited in the sandbox. Small changes in sifting height, sifting rate, and scraping will result in slightly heterogeneous material bulk densities, which will affect the mechanical properties of the sand, and will result in lateral and vertical differences in peak and boundary friction angles, as well as cohesion values once the model is constructed. Initial variations in basal friction are inferred to play the most important role in causing model variability.

Our comparison shows that the human factor plays a decisive role, and even when one modeler repeats the same experiment, quantitative model results still show variability. Our observations highlight the limits of up-scaling quantitative analogue model results to nature or for making comparisons with numerical models. The frictional behavior of sand is highly sensitive to small variations in material state or experimental set-up, and hence, it will remain difficult to scale quantitative results such as number of thrusts, thrust spacing, and pop-up width from model to nature.

Highlights

► A quantitative comparison of thrust wedge models from 15 analogue modeling laboratories is presented. ► Analogue models show variability, most notably for surface slope, thrust spacing and number of forward and backthrusts. ► Model variability is most likely controlled by initial variations in basal friction. ► Our comparison highlight the limits of up-scaling quantitative analogue model results to nature.

Keywords : Thrust wedges, Brittle wedges, Shear zones, Analogue modeling, Benchmarking, Critical taper, Sand, Friction, Cohesion

240 1. Introduction

241

242 Scaled analogue experiments have a long history of modeling geological processes. Analogue
243 models built of materials such as sand, silicone or clay have helped geoscientists to gain
244 insights into the kinematic and dynamic evolution of a wide variety of geological structures.
245 However, as for all models, their results reflect the initial boundary conditions, the choice of
246 materials, the modeling apparatus and the technique of building the model. Unfortunately,
247 many publications on analogue modeling do not adequately record experimental details and
248 material properties, making a detailed comparison of model results among different
249 laboratories simulating similar geological processes difficult. Additionally, experiments are
250 rarely re-run to test the reproducibility and to determine the intrinsic variability of model
251 results.

252

253 Schreurs et al. (2006) were the first to report a direct comparison of scaled analogue
254 experiments to test the reproducibility of model results amongst ten analogue modeling
255 laboratories. One of the two experimental set-ups chosen in their comparison was a brittle
256 thrust wedge experiment (Fig. 1). The experimental set-up, the model-building technique, and
257 the material covering walls and base were all prescribed. However, each laboratory used its
258 own granular material to simulate brittle deformation. Consequently, in the comparison of
259 Schreurs et al. (2006) the material properties can be considered as extrinsic and were a major
260 source of model variability.

261

262 The qualitative evolution of all models was broadly similar (Fig. 2) with the development of a
263 thrust wedge characterized by in-sequence forward thrusting and by minor back thrusting.
264 However, significant quantitative variations existed between models in parameters such as the
265 spacing between thrusts, their dip angles, number of forward and back thrusts and surface
266 slopes.

267

268

269 *INSERT Fig. 1. Experimental set-up used in model comparison experiments by Schreurs et al., (2006). Model*
270 *consists of a 3.5 cm-thick sand layer with an embedded microbeads layer and an overlying sand wedge with a*
271 *surface slope of 10° adjacent to the mobile wall. All walls are covered by Alkor foil. Figure reproduced from*
272 *Schreurs et al. (2006) with permission from the Geological Society of London.*

273

274

275 *INSERT Fig. 2. Model comparison showing crosssections through thrust wedge after 2, 6 and 14 cm of*
276 *shortening. The experimental set-up is shown in Fig. 1. The sections of Bern and IFP Rueil Malmaison are X-ray*
277 *computer tomography (XRCT) images through the center of the model, whereas the remaining sections are*
278 *sidewall observations. Microbeads layer indicated by “m”. Figure modified after and reproduced from Schreurs*
279 *et al. (2006) with permission from the Geological Society of London.*

280

281 In the analogue modeling comparison by Schreurs et al. (2006), each laboratory used its own
282 granular material and differences existed in terms of material properties such as grain size,
283 grain shape and grain size distribution. Hence, we suspect that the resulting inherent
284 variations in material properties between the different labs may have been responsible for
285 differences in the evolution of the experimental models. Lohrmann et al. (2003), for example,
286 determined that the kinematics of thrust wedges is largely a function of their material
287 properties. Differences in the observation techniques used to monitor the evolution of
288 structures also contributed to model variability. Some research groups observed structures
289 through transparent sidewalls, where sidewall friction is highest, whereas other labs used X-
290 ray CT (XRCT) techniques to observe model evolution at the center of the model, where the
291 effects of sidewall frictional stresses are less.

292

293 The outcome of the analogue comparison study by Schreurs et al. (2006) motivated us to
294 propose new comparison experiments, with the aim to better understand the variability
295 between models by discriminating extrinsic versus intrinsic variability. The main differences
296 with the previous analogue model comparison are that in the present study we not only
297 prescribe stringent model-building techniques, but all participating laboratories use exactly
298 the same type of analogue materials for their experiments. By harmonizing boundary
299 conditions and material properties we isolate intrinsic variability related to sources such as
300 inherent randomness or other less obvious conditioning parameters (e.g., air humidity).

301

302 We also decided to choose simple experimental designs using brittle frictional materials only
303 to minimize structural complexity and to better assess structural variability. Our new

304 experiments are thrust wedge experiments that have frequently been performed in the analog
305 modeling community. We choose three different experiments, referred to as experiment 1, 2
306 and 3, respectively. In each of these experiments deformation is imposed by displacement of
307 one mobile, vertical wall. For practical reasons the maximum shortening is limited to 10 cm.
308 This allowed sand box dimensions to be smaller than for larger amounts of shortening, and
309 thereby allowed more labs to participate. Fifteen analogue modeling laboratories joined in this
310 comparison conducting the experiments in their local laboratory environment. In order to
311 isolate the personal impact on experiments, two researchers ran models using the
312 experimental apparatus from the laboratory in Bern. These models are referred to as “Bern”
313 and “GFZ@Bern”, respectively.

314

315 In a companion paper, Buitter et al. (2016) present the results of a comparison of up to 11
316 numerical codes, simulating the same experimental set-ups, with the numerical material
317 properties following the analogue material properties as closely as possible. Major sources of
318 variability here are differences in the implementation of boundary conditions and subtle
319 differences between numerical solvers.

320

321

322 **2. Modeling approach**

323

324 *2.1. Material properties*

325

326 Each laboratory received a shipment of the quartz and corundum sand that is routinely used at
327 the analogue modeling laboratory of the Institute of Geological Sciences at the University of
328 Bern. Laboratories were asked to store the sands in a dry place for at least one month before
329 conducting experiments and to record room temperature and humidity during experimental
330 runs.

331

332 *2.1.1. Physical characteristics*

333

334 The physical characteristics of the sands are summarized in Figure 3. The quartz sand is a
335 natural Triassic sand from a quarry at Schnaittenbach (Germany), whereas the corundum sand
336 is derived from bauxite. The quartz sand has a fairly homogeneous grain size distribution with
337 90% of the grains falling within the 125 - 175 μm fraction. The brown corundum sand has a

338 more heterogeneous grain size distribution with 70% of the grains falling between 88 and 125
339 μm . Bulk density depends both on the material and on the physical handling technique, i.e.
340 whether material is sieved or poured. As shown previously by Krantz (1991), Schellart
341 (2000), Lohrmann et al. (2003), Panien et al. (2006), Gomes (2013) and Maillot (2013) the
342 bulk density of sieved granular materials is higher than the bulk density of poured granular
343 materials. In our experiments, the sands are sieved from a height of 20 cm using prescribed
344 sieve (Appendix A-1) and sieving rates. The bulk densities of quartz and corundum sand
345 sieved from 20 cm height are 1.6 g/cm^3 and 1.9 g/cm^3 , respectively.

346

347

348

349 *INSERT Fig. 3. Physical characteristics of the quartz and corundum sand used in the experiments (modified*
350 *after Panien et al., 2006). Upper and lowermost images are photographs and SEM images, respectively. Width*
351 *of each SEM image is $1740 \mu\text{m}$.*

352

353 *2.1.2. Friction angles and cohesion*

354

355 The mechanical properties of the sands have been determined with a ring-shear tester, model
356 RST-01.pc (Schulze, 2008), at the GFZ in Potsdam. The sands were stored for one month
357 prior to testing to adapt to the air-conditioned environment. Sand storage and ring-shear
358 testing occurred at temperatures of $23 \pm 1^\circ \text{C}$ and atmospheric humidity of $45 \pm 5\%$. The
359 ring-shear tester allows the determination of the internal and boundary friction angles of
360 granular materials at low normal stresses similar to those observed in analog model
361 experiments ($< 20 \text{ kPa}$). The ring-shear tester consists of an annular shear cell holding the
362 tested material, a normal loaded shear lid placed onto the cell, and tie rods measuring the
363 shear stress. Using a ring-shear tester, Lohrmann et al. (2003) could show that granular
364 materials such as quartz sand do not have constant frictional properties. Upon loading the
365 granular materials undergo initially a limited elastic deformation, which is followed by strain
366 hardening preceding failure at peak strength and subsequent strain softening until a stable
367 strength value is reached (Fig. 4). The strain localisation at peak strength is associated with a
368 material compaction-decompaction cycle as inferred from volumetric changes, with
369 maximum dilation rates close to peak strength when faults form (Lohrmann et al., 2003).

370

371 INSERT Fig. 4. Shear stress plotted versus shear strain for quartz sand (modified from Lohrmann et al., 2003;
372 Panien et al., 2006). Strain softening from peak strength to stable strength correlates with dilation of sand.

373

374 The ring-shear tests for measuring internal friction and boundary friction differ in the design
375 of the shear cell and lid. The setup for measuring internal friction ensures that shear
376 displacement occurs entirely within the sand such that only intergranular deformation occurs,
377 whereas the setup for measuring boundary friction ensures that deformation occurs between
378 sand and a surface with controlled roughness, in our case a transparent and super polished
379 self-adhesive foil (brand Alkor-Venilia, article nr. 120010; this foil has been renamed, and is
380 now available as Gekkofix article nr. 11325 from Van Merksteijn Plastics B.V. in the
381 Netherlands, www.gekkofix.nl).

382

383 The physical handling technique used to fill the annular cell of the ring-shear tester was
384 identical to the one used to determine the bulk density and to the one prescribed in our thrust
385 wedge experiments, i.e. material was sifted through a prescribed mesh sieve from c. 20 cm
386 height into the shear cell at a filling rate of c. 250 ml/min. Excess material was subsequently
387 scraped off before assembling shear cell and shear lid.

388

389 Ring-shear measurements were performed at a shear velocity of 3 mm/min for 4 minutes at a
390 given normal load. For each test, measurements were done for different normal stresses
391 ranging from c. 500 Pa to c. 2240 Pa in steps of c. 435 Pa, and for each particular normal
392 stress, peak strength and stable strength values were determined. Each ring-shear test was
393 repeated three times for both quartz sand and corundum sand.

394

395 Measured shear stress values at peak strength and at stable strength are plotted against the
396 applied normal stresses and a linear regression analysis is applied to the data, to obtain the
397 friction coefficient, μ , which corresponds to the slope of the line and the friction angle, ϕ ,
398 which is $\tan^{-1}\mu$. The cohesion is the linearly extrapolated value at zero normal stress. We
399 report the range of friction angles and (apparent) cohesion values in Table 1.

400

401

402 INSERT Table 1. Range of mechanical properties of quartz and corundum sand obtained with a ring-shear
403 tester. Values are rounded to nearest degree for friction angles and to nearest whole number for cohesion. n is
404 number of ring-shear tests at normal stresses ranging from c. 500 to 2240 Pa.

405
406
407
408
409
410
411
412
413
414
415
416
417
418
419

The angle of internal friction at peak strength (ϕ_p) of the tested quartz and corundum sand are about 35-36°. The angles of internal friction at stable strength (ϕ_s) are in both cases lower, with values around 30-31°. The angle of boundary friction (ϕ_b) varies more for quartz sand on Alkor foil, with values between 15° and 21°, than for corundum sand on Alkor foil with values of $24^\circ \pm 1^\circ$. At the range of applied normal stresses the cohesion at peak strength (C_p) for both granular materials is in the order of a few tens of Pa. Boundary cohesion values (C_b) range from 14 to 141 Pa for quartz sand and from 23 to 44 Pa for corundum sand. The large spread in cohesion values is due to the linear extrapolation to zero normal stress on shear stress versus normal stress curves. Strain softening corresponds to the weakening of the shear zone after its formation. By comparing the mean values of the peak internal friction coefficient and the stable friction coefficient for each granular material, the mean strain softening can be determined, which amounts to c. 15-20% for both quartz and corundum sand.

420
421
422
423
424
425
426
427
428

Panien et al. (2006) used the same ring-shear tester at identical laboratory climatic conditions to determine the material properties of the same quartz and corundum sand as used in this model comparison. Their filling procedure (filling height and rate) is identical to ours, albeit with a slightly different sieve. The obtained values for repeated measurements correspond closely to ours. Their mean values for ϕ_p of quartz and corundum sand are 36° and 37°, respectively and their mean values for ϕ_s are 31° and 32°, respectively. Using the same Alkor foil, Panien et al. (2006) also found that boundary friction angles at peak strength and at stable strength are lower for quartz sand than for corundum sand.

429
430

2.1.3. *Dilation and elasticity*

431
432
433
434
435
436
437

Deformation of the granular materials used in our experiments occurs by localization along shear zones in combination with dilation. The dilation angles at peak strength for our dry quartz and corundum sand are difficult to determine with a ring-shear tester. It requires measurements of the changes in volumetric strain, but the volumetric strain depends on the width of the initial shear zone that forms. Assuming an initial shear zone width of about 10

438 times the average grain size (Panien et al., 2006), we obtain very small dilation angles of less
439 than 2° . Measurements of shear zone formation in dry sands indicate that dilation approaches
440 zero once the shear zone has formed (Lohrmann et al., 2003; Bernard et al., 2007).

441
442 The elastic behaviour of the granular materials is characterized by at least two elastic
443 parameters, e.g. Young's modulus E and Poisson's ratio ν . Young's modulus is the ratio of
444 uniaxial stress and strain: $E = \sigma/\epsilon$, while Poisson's ratio is the negative ratio of transverse
445 strain (ϵ_x) to longitudinal strain (ϵ_z) under conditions of uniaxial stress, i.e. $\nu = -\epsilon_x/\epsilon_z$. Another
446 elastic parameter is the bulk modulus K defined by the ratio of mean stress over volumetric
447 strain. K is related to E and ν and can be expressed as $K = E/(3(1-2\nu))$. Importantly, one has
448 to differentiate between the elasticity of individual granular particles (which is in the order of
449 tens of GPa for sand) and the elasticity of the bulk solid, i.e. the structure made by many
450 grains in contact, which is generally much lower and the one relevant in our modelling
451 approach.

452
453 The bulk moduli (K) of dry quartz and corundum sand were measured performing loading-
454 unloading cycles (maximum load: 20 kPa) on sieved sand samples with a uniaxial confined
455 compression tester at GFZ Potsdam. The values vary depending on the degree of compaction,
456 which increases mainly during the first few loading-unloading cycles. Linear regression
457 analysis of the stress-strain curves (up to a strain of 0.00003) during loading of the first ten
458 cycles suggests an effective bulk modulus of around 200 MPa for both sands under laboratory
459 conditions. Assuming a Poisson's ratio, ν , of about 0.25 results in a Young's modulus E of
460 300 MPa. Though orders of magnitude smaller than for single grains these values are so high
461 that elastic deformation in the experiments is expected to be below the detection threshold of
462 even sophisticated optical strain measurement systems (e.g. microns when applying subpixel-
463 resolution particle image velocimetry, Adam et al., 2005). Stress is therefore expected to
464 accumulate and relax without obvious deformation in sandbox experiments. This is in contrast
465 to more elastic modelling approaches where proper scaling of elasticity from nature to the
466 analogue model yields observable elastic effects (Rosenau et al., 2009).

467

468

469 *2.2. Brittle thrust wedges*

470

471 The formation of fold-and-thrust belts and accretionary wedges in compressional settings is
472 comparable to the process of forming a wedge of snow in front of a moving bulldozer with a
473 taper angle described by the critical taper theory (e.g. Davis et al., 1983; Dahlen et al., 1984;
474 Zhao et al., 1986; see Buiter et al., 2012 for an extensive review of brittle compressional
475 wedge models). The material being pushed will reach an equilibrium angle, the so-called
476 critical taper angle, which is the sum of the surface slope angle (α) and the basal dip angle of
477 the wedge (β). The critical taper angle depends on the material properties within the wedge,
478 the pore fluid pressure and the strength of the decollement along the base of the wedge.

479

480 Under the assumption that the material deforms according to the Coulomb failure criterion
481 and that the base of the wedge is cohesionless (i.e., $C_b = 0$), the critical taper theory permits
482 the derivation of the critical taper angle for a dry sand wedge (pore fluid pressure is zero)
483 knowing the angle of internal friction, the internal cohesion and the angle of basal friction
484 (Fig. 5). Dahlen et al. (1984) show that a cohesionless wedge results in a perfectly triangular
485 form, whereas a wedge with a constant internal cohesion will acquire a concave upward
486 surface.

487

488 Fig. 5 shows wedge stability fields for cohesionless and internal cohesive sands with frictional
489 properties that closely correspond to those obtained from ring-shear tests on our sands: for a
490 cohesionless sand at peak strength and at stable strength, and for a cohesive sand at peak
491 strength with depth-dependent internal cohesion (Buiter et al., 2016).

492

493 *INSERT Fig. 5. Zoom of critical taper curves for cohesionless sand at peak strength ($\phi_p = 36^\circ$, $\phi_b = 15^\circ$ and $C =$
494 0 Pa), cohesionless sand at stable strength ($\phi_s = 31^\circ$, $\phi_b = 15^\circ$ and $C = 0 \text{ Pa}$), and a cohesive sand at peak
495 strength with depth-dependent cohesion ($\phi_p = 36^\circ$, $\phi_b = 15^\circ$ and $C = 20 \text{ Pa cm}^{-1}$ times z , with $z = \text{depth}$, following
496 Zhao et al. (1986)).*

497

498

499 Wedges in the stable field will slide stably without internal deformation as long as no new
500 material is accreted. This is our experiment 1, which has an initial wedge shape with a
501 horizontal base and a 20° surface slope (Fig. 5). Unstable, subcritical wedges will deform
502 internally upon compression towards the critical taper angle. Our experiment 2 and 3 models
503 with initial horizontal layering start out as subcritical wedges (Fig. 5).

504

505 2.3. General model building procedure

506

507 Although each lab used its own experimental apparatus, all labs applied the same type of self-
508 adhesive Alkor foil to cover the base and the four vertical walls of their experimental
509 apparatus in order to guarantee identical shear stresses at the boundaries. In addition, each lab
510 received a detailed document outlining the prescribed model-building techniques including
511 details on mesh sieve structure for model construction and leveling techniques (Appendix A).
512 The model was built by sifting sand through a sieve with specified mesh sieve from a height
513 of 20 cm at a filling rate of c. 250 ml/min. This procedure is identical to the one used to fill
514 the test cell during ring-shear test measurements. The minimum width of the model (measured
515 along the mobile wall) was prescribed at 20 cm. Model widths as well as laboratory
516 temperature and relative humidity are shown in Table 2.

517

518

519 *INSERT Table 2. Overview of laboratory climatic conditions and model widths. Most laboratories performed*
520 *experiments 2 and 3 twice, and range of values for room temperature and relative humidity are indicated.*
521 *Exceptions to the prescribed modeling procedure are also given.*

522

523

524 2.4. Model analysis

525

526 We analyse our models in a qualitative way by comparing cross-sectional views and top
527 views and in a quantitative way by cross section measurements. As boundary stresses created
528 significant drag of structures along the sidewalls, our visual comparison is done for sections
529 away from the sidewalls. Consequently, for models analysed in a conventional way by
530 physically cutting the model, we only show cross sections through the final stage of
531 deformation. However, for models analysed by X-ray computed tomography (XRCT) we
532 show the cross-sectional evolution at successive increments of mobile wall displacement,
533 hereafter termed shortening.

534

535 Our quantitative analysis consisted of measuring surface slope (Fig. 6a), thrust spacing
536 between forward thrusts (Fig. 6b), dip angle of newly formed forward thrusts at base, mid and
537 top (Fig. 6c), thrust initiation (i.e. at how much shortening a particular thrust forms) and
538 number of thrusts at the end of the experiment. We define a thrust as formed when it shows a

539 small, visible offset in cross section. As in the previous model comparison (Schreurs et al.,
540 2006), two of us (Guido Schreurs and Susanne Buitert) performed the quantitative analysis by
541 measuring the aforementioned parameters in the same manner and averaging the obtained
542 values. In general the differences between the two measurers were small, with average
543 difference in slope values of 1-2° and maximum difference in dip values of 3°. Also
544 differences in measured distance values were generally small. In models analysed by XRCT
545 all parameters were measured using cross-sectional images taken at 0.5 cm increments of
546 displacement for Experiment 1, and at 0.2 cm increments of displacement until 1 cm and
547 subsequently at 0.5 cm increments until 10 cm shortening for Experiments 2 and 3.

548

549

550 *INSERT Fig. 6. Schematic illustration of measurements of a) surface slope, b) forward thrust spacing, and c)*
551 *thrust dip angles. Surface slope is measured as the best fitting line through the valleys (Stockmal et al., 2007)*
552 *and can only be determined once at least 2 thrusts have formed. Thrust spacing is measured horizontally from a*
553 *newly initiated in-sequence forward thrust to the previously formed forward thrust.*

554

555

556 To document lateral variations of structures, we compared sections at five different positions.
557 As model width varied between laboratories, we defined the five sections in terms of along-
558 strike model width at 25%, 50% - 2 cm, 50%, 50% + 2 cm, and 75% positions (see Fig. 7).

559

560

561 *INSERT Fig. 7. Top view photograph illustrating position of cross sections at 25% (1), 50%-2 cm (2), 50% (3),*
562 *50% + 2 cm (4), and 75% (5) of model width (measured parallel to mobile wall, which moves here from bottom*
563 *to top). Model width is 80 cm in this particular experiment.*

564

565

566 **3. Experiment 1**

567

568

569 *3.1. Experiment 1: Model set-up*

570

571 In the first experimental set-up, a quartz sand wedge with a horizontal base ($\beta = 0^\circ$) and a
572 surface slope (α) of c. 20° was constructed adjacent to the mobile wall (Fig. 8). The height of
573 the wedge immediately adjacent to the mobile wall is 3 cm.

574

575

576 *INSERT Fig. 8. Model set-up for experiment 1.*

577

578

579 Model building consisted of two steps (Fig. 9). In a first step quartz sand was sieved in the
580 sandbox partly sloping towards the fixed wall (Fig. 9a). In a second step a template with a 20°
581 slope-angle was attached onto each sidewall and excess material was scraped towards the tip
582 of the wedge and taken out (Fig. 9b). Adjacent to the fixed wall, there was at least 5 cm space
583 where no sand covered the base. The model was shortened 4 cm by inward movement of the
584 mobile wall. Eleven analogue modeling laboratories ran experiment 1 once.

585

586

587

588

589 *INSERT Fig. 9. Model building procedure for experiment 1 shown in cross section. A template with the shape of*
590 *the final wedge is attached on top of each sidewall to guide the scraper (see Appendix A-2). Stippled line*
591 *indicates sand wedge before final scraping.*

592

593

594 *3.2. Experiment 1: Results*

595

596 Three intrinsic material parameters are important in the critical taper theory: the internal peak
597 friction, internal cohesion, and basal friction. Of these three parameters, the basal friction of
598 quartz sand is the least constrained, varying between 15 and 21° (Table 1). However, even
599 when taking into account this uncertainty, the quartz sand wedge of experiment 1 is well
600 within the stable domain. Hence, the wedge should slide stably without internal deformation
601 and consequently the surface slope should remain constant throughout the experiment.

602

603 All experiment 1 models do conform to the critical taper theory and are stable. The quartz
604 sand wedge is translated along the horizontal base and is not affected by internal localized
605 deformation. Apart from a slight slope change in the extreme front region of the wedge in a
606 number of experiments, the overall surface slope remains constant (Fig. 10 and 11).

607

608

609

610 *INSERT Fig. 10. Evolution of experiment 1 model run at Bern after 0, 2 and 4 cm of shortening (a) XRCT*
611 *sections through centre of model, (b) top view photographs of model.*

612

613

614 *INSERT Fig. 11. Cross sections through centre of experiment 1 models after 4 cm of shortening. Sections of*
615 *Bern, GFZ@Bern, and IFP are XRCT images. Note that Toronto and Uppsala laboratories added extra sand on*
616 *the wedge before cutting cross section.*

617

618 **4. Experiment 2**

619

620

621 *4.1. Experiment 2: Model set-up*

622

623 In experiment 2 alternating horizontal layers of quartz and corundum sand are shortened by
624 inward movement of a mobile wall (Fig. 12). Both the base and the surface of the model are
625 horizontal ($\alpha = \beta = 0^\circ$) and the “wedge” starts in the unstable field (Fig. 5). The minimum
626 length of the undeformed model, measured parallel to the movement direction of the mobile
627 wall, was 35 cm. The model had an initial thickness of 3 cm and directly overlies the base of
628 the model. Total shortening of the model by inward displacement of the mobile wall was 10
629 cm. No exit slot existed below the mobile vertical wall and the base of the model.

630

631

632 *INSERT Fig. 12. Model set-up for experiment 2.*

633

634 Fourteen laboratories participated in experiment 2, running a total of 25 models, of which five
635 were analysed by XRCT.

636

637

638 *4.2. Experiment 2: Results*

639

640 *4.2.1. Evolution of models analysed by XRCT*

641

642 Fig. 13 shows the cross-sectional evolution through the centre of five thrust wedge models
643 analysed by XRCT after 1, 2, 6 and 10 cm of shortening. Movies showing additional stages in
644 the cross-sectional evolution are given in the journal’s repository. Shortening is
645 accommodated by forward thrusts, which propagate in-sequence towards the foreland, and by
646 back thrusts.

647

648 The first pop-up structure develops between 0.5 and 1 cm of shortening (Fig. 14) adjacent to
649 the mobile wall. The dip of the first forward thrust steepens slightly upwards, with dips
650 varying between 22° and 25° at the bottom, between 27° and 31° at the middle, and between
651 26° and 32° at the top (Fig. 15a). The back thrust of the first pop-up structure generally dips

652 steeper than the forward thrust, in particular near the base of the model. The variation in dip
653 of the first-formed back thrust is large, with dip angles between 26° and 46° at the bottom,
654 and between 27° and 45° at the middle and at the top (Fig. 15b). The width of the pop-up at
655 the surface varies because of the considerable variation in dip of the back thrust. Models with
656 a steep back thrust (Bern 2B and IFP 2A) have a narrower pop-up width than models with a
657 shallow-dipping back thrust (Fig. 13; 1 cm of shortening).

658

659 After 2 cm of shortening a second back thrust has formed in all models, except in model Bern
660 2A. The first-formed forward thrust takes up most of the initial shortening and the first-
661 formed back thrust is displaced along it (Fig. 13; 2 cm of shortening). A second in-sequence
662 forward thrust forms between 3 and 5.5 cm of shortening and further in-sequence forward
663 thrusts develop with progressive shortening. The spacing to the previously formed forward
664 thrust at the moment of initiation of a new forward thrust tends to increase for subsequent
665 thrusts (Fig. 14b). In general the dip of newly formed in-sequence thrusts near the base of the
666 model becomes shallower with progressive deformation

667

668 A second pop-up structure forms in all XRCT models, albeit at different stages: at 5.5 cm of
669 shortening for Bern 2A, at 6.5 cm for GFZ@Bern, and at 9 cm for Bern 2B, IFP 2A and IFP
670 2B. Back thrusts associated with this second pop-up generally cross-cut earlier-formed, now
671 inactive forward thrusts.

672

673

674 *INSERT Fig. 13. Cross-sectional evolution through centre of experiment 2 models after 1, 2, 6 and 10 cm of*
675 *shortening as observed in XRCT images.*

676

677 The surface slope evolution of the wedge for models analysed by XRCT is shown in Fig. 16
678 Oscillations in surface slope angles reflect the formation of new thrusts. All models except
679 Bern 2A show these oscillations. The Bern 2A model shows instead a steady increase in
680 surface slope.

681

682

683

684

685 *INSERT Fig. 14. Quantitative comparison of experiment 2 models analysed by XRCT. (a) Amount of shortening*
686 *at which a forward thrust forms at centre of model. (b) Spacing to previously formed forward thrust at the*
687 *moment of initiation of a new, in-sequence forward thrust.*

688

689

690 *INSERT Fig. 15. Dip angles of successive in-sequence forward (a) and back thrusts (b) in centre of experiment 2*
691 *XRCT models, measured at top, middle and bottom.*

692

693

694 *INSERT Fig. 16. Surface slope evolution at centre of experiment 2 XRCT models. Only values that could be*
695 *reliably measured in XRCT images are given.*

696

697 4.2.2. Final deformation stage

698

699 Cross sections through the centre of all experiment 2 models after 10 cm of shortening show a
700 series of forward and back thrusts directly adjacent to the mobile wall (Fig. 17). In addition,
701 most models show a second pop-up structure that formed in front. However, the models of
702 Kyoto, Parma, Piscataway 2A and 2B, and Stanford 2A lack this second pop-up structure and
703 consequently have higher surface slopes.

704

705

706 *INSERT Fig. 17. Cross sections through centre of experiment 2 models after 10 cm of shortening. Width of each*
707 *panel shown is 25 cm. Note that some labs added a layer of sand before cutting the model. Cross sections from*
708 *Lille 2A and 2B are at 50%-2cm position. Image quality of cross sections from Stanford 2A and 2B was not good*
709 *enough for reproduction.*

710

711 The top views for experiment 2 after 10 cm shortening are shown in Fig. 18. Approaching the
712 sidewalls of the models, thrusts are convex to the hinterland with the thrust wedge becoming
713 narrower and steeper. Along-strike structural changes are present in all models away from the
714 sidewalls, with curved thrust segments and along-strike merging of thrusts. The along-strike
715 changes are also well visible in the cross-sectional wedge geometries shown for 5 different
716 locations in Fig. 19.

717

718 The surface slope is measured in cross sections at the 25%, 50% and 75% positions and varies
719 between 4° and 24° (Fig. 20). Surface slopes measured along one sidewall (0% position) are

720 shown for comparison and are, for one particular model, generally considerably higher than
721 those measured at the other three positions. Variations in surface slope along strike within one
722 model are generally small, with most models showing along-strike differences between
723 maximum and minimum surface slope of less than 4° (Fig. 20). Only the Lille 2B model and
724 Melbourne 2A model have higher along-strike differences of 6° and 11°, respectively.

725

726 The number of thrusts has also been measured at the 25%, 50% and 75% positions (Fig. 21).
727 Models have between 3 and 5 forward thrusts at the end of the experimental run (10 cm of
728 shortening), except Mexico 2A and 2B, and Piscataway 2A, which have a higher number of
729 thrusts (up to 9), and Bern, which has only two forward thrusts (Fig. 21a). The number of
730 backthrusts varies between 1 and 9, and in comparison with the forward thrusts, there is an
731 overall higher along-strike variability in the number of backthrusts within one particular
732 model.

733

734

735 *INSERT Fig. 18. Top views of experiment 2 models after 10 cm of shortening showing along-strike structural*
736 *variability. Movement of mobile wall is from bottom to top Note that Lille 2A and 2B models have a grid of*
737 *corundum sand imprinted on the surface, whereas Mexico 2A and 2B models used prescribed sand mixed with*
738 *dark sand particles. All photos are shown at the same scale, given in the top left photo.*

739

740

741 *INSERT Fig. 19. Cross sections after 10 cm shortening for experiment 2 models at positions 25%, 50%-2 cm,*
742 *50%, 50%+2 cm and 75% (see Fig. 6) showing along-strike structural variability. Note that some laboratories*
743 *added a post-kinematic sand layer before wetting and sectioning.*

744

745 *INSERT Fig. 20. Surface slope after 10 cm of shortening at 25%, 50% and 75% positions for experiment 2*
746 *models. The surface slope could not be reliably measured on all cross-sectional images. Surface slopes for Lille*
747 *2A and Lille 2B models were measured at 50%-2cm position. Numbers above symbols indicate difference*
748 *between maximum and minimum slope angle within one particular model and are only given for those models in*
749 *which the surface slope could be determined at all three positions. Surface slope values along one sidewall (0%*
750 *position) are given for comparison and are generally higher.*

751

752

753 *INSERT Fig. 21. Number of forward and back thrusts at 25%, 50% and 75% position after 10 cm of shortening*
754 *for experiment 2 models. Numbers above symbols indicate along-strike differences in number of thrusts and are*
755 *only given for those models, in which thrusts could be reliably determined at all three positions.*

756

757

758 4.2.3. Model similarities and variability

759

760 The experiment 2 models share a number of similarities:

761

762 (1) the development of forward thrusts propagating in-sequence and the formation of back
763 thrusts,

764 (2) the formation of a first pop-up adjacent to the mobile wall forming in all models before 1
765 cm of shortening

766 (3) the fairly uniform dip of the first forward thrust, which steepens slightly upwards,
767 resulting in a slightly listric thrust plane

768 (4) the first backthrust that forms close to the mobile backwall dips steeper than the first
769 forward thrust

770 (5) in top views thrust wedges are curved with a convex to the hinterland shape. Sidewall
771 friction results in a narrower and steeper wedge immediately along the sidewall when
772 compared to sections through the center of the model

773

774 However, our quantification of experiment 2 model results shows that there are also important
775 variations, notably:

776

777 (1) The number of forward thrusts and backthrusts that formed after a certain amount of
778 shortening is variable when comparing all models (Fig. 14a). For example, the number of
779 forward thrusts through the centre of the model after 10 cm shortening varies between 2 and
780 9, whereas the number of back thrusts varies between 1 and 9 (Fig. 21). Variability in the
781 number of thrusts within one particular model is less with a difference in number of thrusts
782 along strike varying from 0 to 3 (Fig. 21).

783 (2) The surface slope of the thrust wedge is highly variable. Whereas four out of the five
784 models analysed by XRCT show an oscillating behaviour in surface slope, reflecting new
785 thrust formation, Bern 2A model shows a steady increase in surface slope. After 10 cm of
786 shortening the surface slope through the centre (50% position) of all models varies between 4°
787 and 24°.

788 (3) Not all models develop a second pop-up structure. In case a second pop-up forms, the
789 associated back-thrusts cut in most cases previously formed forward thrusts in the hinterland.

790

791 The variations in overall wedge geometry result from local scale variations in thrust dips.
792 Notably, the variability in dip of newly formed back thrusts is large, with dip angles ranging
793 from 26° to 50°, and also the width of the initial pop-up structure through the centre of the
794 models (Fig. 13) varies considerably due to varying dip angles of forward and in particular
795 back thrusts.

796

797

798 *4.3. Experiment 2 model and the critical taper theory*

799

800 The internal peak friction angles of the quartz and corundum sand used in experiment 2 are
801 nearly identical (Table 1) and a value of $\phi_p = 36^\circ$ is considered a good approximation for the
802 entire sand wedge. If we take into account the uncertainty in the basal friction angle (ϕ_b) of
803 the quartz sand layer, ranging between 15° to 21°, the analytical solutions derived from the
804 critical taper theory indicate that the critical taper angle, which equals the surface slope for
805 experiment 2 with a horizontal base, would be between c. 4 and 6° (taking only the lowest of
806 the two permissible critical taper angles) for a sand wedge with depth-dependent cohesion of
807 20 Pa cm⁻¹.

808

809 The initial horizontally layered models of experiment 2 start out as a sub-critical wedge and
810 deform by in-sequence thrusting. After 10 cm of shortening sections through the centre of the
811 models show a wide spread in surface slope, ranging between 4° and 24°. Only the surface
812 slopes of models GFZ@Bern, Taipei 2A, Uppsala 2B, with slopes of 5°, 6°, and 4°,
813 respectively, are within the predicted range of values for a cohesionless wedge. The fact that a
814 few models do reach a critical taper could suggest that at 10 cm shortening the wedges are at
815 the verge of transition from an immature, subcritical wedge to a critical one.

816

817 The discrepancy between most model surface slopes and analytical predictions of the critical
818 taper theory are possibly related to a combination of factors described below:

819

820 (1) After 10 cm shortening, the surface slope in the deforming thrust wedge might not
821 have yet stabilised and more shortening might be needed in order for the sand wedge
822 to achieve steady state and reach its critical taper. It has also to be kept in mind that the

823 critical taper theory assumes a perfect, infinite length wedge, with a sharp tip. Here,
824 the wedge tip is replaced by a flat layer of thickness (3 cm), which is as much as half
825 the maximum wedge height (about 6 cm) at the end of experiments. Departures from
826 the assumptions of the theory are therefore substantial.

827

828 (2) Compaction and dilation of sand during localization of deformation along faults,
829 which is not considered in the critical taper theory, also affects the frictional strength
830 of the wedge. Lohrmann et al. (2003) show that the frictional strength of the wedge
831 changes as faults form in the wedge, and that the behaviour of the wedge is controlled
832 by the frictional strength of these faults, which have angles of stable sliding. Hence, in
833 our case it would be more appropriate to take the internal angle of friction at stable
834 sliding strength (ϕ_s) which is 31° , instead of the internal angle of friction at peak
835 strength (ϕ_p), which is c. 36° , and also the boundary friction angle at stable sliding
836 strength of quartz sand (ϕ_{bs}), which is between 9 and 14° instead of the boundary
837 friction angle at peak strength (ϕ_b), which is between 15 and 21° (Table 1). Using
838 stable sliding internal friction values (neglecting cohesion), the critical surface slopes
839 range between 3° and 5.2° , i.e. essentially the same as using the peak values (3° to 6°),
840 because the loss of strength in the bulk material and at the base partly counteract each
841 other.

842

843 (3) Ring-shear tests show that our analog model materials have a basal cohesion that is
844 not taken into account in the critical taper theory. With uniform basal and peak
845 cohesion, a critical taper would assume a concave surface shape. Estimates using the
846 limit analysis method (Mary et al., 2013b) yield surface slopes around 5° to 6° for $\phi_p =$
847 36° , $\phi_b = 15^\circ$, $C_p = 20$ Pa and $C_b = 15$ Pa ; and in a higher range of 11° to 13° for $\phi_p =$
848 36° , $\phi_b = 21^\circ$, $C_p = 70$ Pa and $C_b = 140$ Pa. Therefore, cohesion of the materials
849 could in part explain the discrepancy with the critical taper theory.

850

851

852 **5. Experiment 3**

853

854 *5.1. Experiment 3: Model set-up*

855

856 In the set-up of experiment 3 a thin rigid sheet, 1 mm thick, and 12 cm in length is attached to
857 the mobile wall and underlies part of the model. The tip of the rigid sheet has a perpendicular
858 cut. Displacement of the mobile wall creates a moving basal velocity discontinuity where
859 deformation localizes away from the mobile wall during shortening of the model (Fig. 22).
860 The thin sheet is covered by Alkor foil, as are the base and the four vertical walls of the
861 experimental apparatus. The model consists of three 1-cm-thick layers of quartz and
862 corundum sand. Minimum prescribed model length parallel to the movement direction is 35
863 cm.

864

865 *INSERT Fig. 22. Model setup for experiment 3.*

866

867 Experiment 3 was done by 14 laboratories, and a total of 22 models were run, of which five
868 were analysed by XRCT.

869

870

871 *5.2. Experiment 3: Results*

872

873 *5.2.1. Evolution of models analysed by XRCT*

874

875 The cross-sectional evolution through the centre of experiment 3 models reveals that in all
876 five models analysed by XRCT a pop-up structure has formed at the tip of the moving basal
877 sheet after 1 cm of shortening (Fig. 23). At this stage the overall dip of the backthrust is
878 somewhat steeper than the forward thrust (Fig. 24). Both forward thrust and backthrust have a
879 slightly listric shape with dips between 26° and 32° at the top, and between 17° and 23° near
880 the base (Fig. 25).

881

882 With continuing shortening the first-formed forward thrust is advected upward along the
883 backthrust, and new in-sequence forward thrusts initiate at the base, propagate upward and
884 either merge with the pre-existing forward thrust at depth or reach all the way to the surface.
885 This process is repeated during continuing shortening: previously formed forward thrusts are
886 displaced along the backthrust and new in-sequence forward thrusts form in the footwall. The
887 dip of new in-sequence forward thrusts is in general shallower than the first-formed forward
888 thrust and their dip near the surface varies between 22° and 27° .

889

890

891 *INSERT Fig. 23. Cross sections at 1, 2, 6 and 10 cm for all experiment 3 models analysed by XRCT.*

892

893

894 *INSERT Fig. 24. Dip of successive forward thrusts at time of initiation through centre of model, measured at*
895 *bottom, middle and top in experiment 3 XRCT models.*

896

897

898 *INSERT Fig. 25. Evolution of surface slope through centre of experiment 3 XRCT models. The lines connecting*
899 *measurements illustrate the oscillating behaviour of the surface slope, which tends to become less with*
900 *increasing shortening. Numbers above symbols indicate the difference in maximum and minimum surface slope*
901 *between the five models at a specific shortening increment.*

902

903 After 3.5 cm of shortening, the surface slope of the five XRCT models, measured in sections
904 through the centre of the model, varies between 5° and 16° (Fig. 25). During initial shortening
905 the surface slope in each model increases, and then shows an oscillating behaviour which
906 tends to become less important with increasing shortening. Comparing the XRCT models
907 indicates that the spread in surface slope values tends to diminish with increasing shortening.
908 At 10 cm of shortening surface slopes range between 16° and 22° (Fig. 25).

909

910 *5.2.2. Final deformation stage*

911

912 A comparison of all cross sections at the 50% position after 10 cm shortening (Fig. 26) shows
913 very similar geometries: a series of forward thrusts with relatively small, individual offsets,
914 and one backthrust with a large offset, except for the Lille and Melbourne 3A models which
915 show an additional backthrust.

916

917 Top views of all models indicate slight lateral variations in the strike of forward thrusts and
918 lateral merging of forward thrusts (Fig. 27). In top views, both forward thrusts and
919 backthrusts have a convex to the hinterland shape as a result of friction along the sidewalls.

920

921 Cross sections at five different positions after 10 cm of shortening (Fig. 28) show minor
922 lateral variations, which mainly relate to surface slope and number of forward thrusts.

923

924 The surface slope for all models at the 25%, 50% and 75% positions is quite uniform, with
925 values between 16° and 24° (Fig. 29). The Uppsala 2B model is the only exception. It has a
926 shallower surface slope ranging between 12° and 14° at all three positions. Lateral differences
927 in surface slope within one model are minor, mostly only between 1 and 3°. Only the Bern 3B
928 and Lille models show larger along-strike variations with differences in values of surface
929 slope up to 5°.

930

931 The number of forward thrusts was determined in cross sections at the 25%, 50% and 75%
932 positions and only thrusts that produced a noticeable offset at the surface were considered
933 (Fig. 30). The number of forward thrusts varied between 4 and 9 among all models. Within
934 one particular model the difference in thrust number along strike is small, between 1 and 2 for
935 most models, with only the Bern 3B, GFZ@Bern and Piscataway 3A models showing a
936 difference in thrust number of 3.

937

938

939 *INSERT Fig. 26. Cross sections after 10 cm of shortening through centre of experiment 3 models. Cross section*
940 *of Stanford 3A is not shown, because image quality was insufficient for reproduction.*

941

942

943 *INSERT Fig. 27. Top views after 10 cm of shortening for experiment 3 models. Lille model has a surface grid of*
944 *corundum sand.*

945

946

947 *INSERT Fig. 28. Cross sections after 10 cm shortening for experiment 3 models at positions 25%, 50%-2 cm,*
948 *50%, 50%+2 cm and 75% of model width (see Fig. 7).*

949

950

951 *INSERT Fig. 29. Surface slope after 10 cm of shortening at 25%, 50% and 75% position for experiment 3*
952 *models*

953

954

955 *INSERT Fig. 30. Number of forward thrusts after 10 cm of shortening at 25%, 50% and 75% position for*
956 *experimental 3 models. Note that only those thrusts were considered that produced a noticeable offset at the*
957 *surface. The number of thrusts in Stanford 3A and 3B models could not be reliably determined due to poor*
958 *image quality.*

959

960

961

962 5.2.3. Model similarities and differences

963

964 Visual comparison of all experiment 3 models shows that the evolution of structures both in
965 cross section and top view is very similar. A pop-up structure forms initially above the
966 moving basal velocity discontinuity, with subsequent in-sequence forward thrusts being
967 advected along the backthrust and becoming successively inactive when a new forward thrusts
968 forms at the tip of the moving basal sheet. The backthrust, however, remains active
969 throughout the shortening and accommodates much more fault displacement than individual
970 forward thrusts. Nearly all models have only one backthrust and between 4 and 9 forward
971 thrusts.

972

973 The surface slope of the models at 10 cm shortening varies between 12 and 24°. These values
974 are well above the predicted critical taper angles (c. 4-6°) for sand with $\phi_p = 36^\circ$, ϕ_b between
975 15° and 21° and $C = 0$. However, the particular set-up of experiment 3 probably does not
976 warrant a direct comparison with the critical taper theory. The critical taper theory accounts
977 for a situation in which the velocity discontinuity (between mobile wall and material) is
978 adjacent to the wedge, whereas in experiment 3 the velocity discontinuity is below the sand
979 wedge. The pop-up that forms at the tip of the rigid basal sheet results in a wedge of material
980 in the footwall of the backthrust that remains undeformed and is passively displaced along
981 with the basal sheet. As a result the backthrust remains active throughout the experiment,
982 advecting material and forward thrusts upward, but at the same time preventing propagation
983 of forward thrusts away from the velocity discontinuity towards the foreland.

984

985

986 **6. Discussion of model results**

987

988 *6.1. The effect of sidewall friction*

989

990 Sidewall friction in sandbox models has an influence on thrust wedge geometry (e.g. Costa
991 and Vendeville, 2004; Schreurs et al., 2006; Souloumiac et al., 2012). Thrust wedges are
992 generally narrower and steeper near the sidewalls and shallower and wider in the centre of the

993 model. This is caused by sidewall drag causing rotation of the stress field within the sand.. In
994 our models with fixed sidewalls and a mobile backstop, the lateral effects due to sidewall
995 friction result in a convex-to-the-backstop shape of the thrust wedge in top view. This is
996 largely consistent with the analysis of Souloumiac et al. (2012), who measured the effect of
997 sidewall friction in experiments in which a sand wedge undergoes plane-strain shortening.
998 They varied the surface S_L of sand in contact with the sidewalls, and the surface S_B in contact
999 with the base plate of the sandbox. For initial ratios S_L/S_B between 0.1 and 0.35, Souloumiac
1000 et al. (2012) found that sidewall friction during shortening of the sand wedge causes thrust
1001 curvature near the side walls, whereas for S_L/S_B ratios < 0.1 sidewall friction has negligible
1002 effects. At S_L/S_B ratios > 0.35 , thrusting occurs at different locations throughout the box,
1003 revealing a major experimental bias (Souloumiac et al., 2012). For the experiment 2 and 3
1004 models presented here, S_L/S_B varies between 0.075 and 0.3, and all models show thrust
1005 curvature near the sidewalls (Figs. 18 and 29). The fact that the Bern and IFP models, with
1006 S_L/S_B ratios < 0.1 still show thrust curvature near the sidewalls might be related to the
1007 difference in the nature of the walls, i.e. foil-covered walls in the experiments presented here
1008 and glass walls in the experiments of Souloumiac et al. (2012). From an inspection of top
1009 views, we estimate that sidewall friction only plays a role on thrust wedge curvature until c. 5
1010 cm away from the sidewalls. All our quantified parameters are measured in sections that are at
1011 least 5 cm away from the sidewalls (except IFP exp 1), and hence our results are not expected
1012 to be affected by the effects of sidewall friction.

1013
1014 Friction on the moving back wall also has an effect. In the previous analogue model
1015 comparison (Schreurs et al., 2006, Fig. 2b), six models developed a pop-up against the back
1016 wall, and two models developed a single forward thrust rooted at the back wall-base plate
1017 corner. Souloumiac et al. (2010, Fig. 11 and 14) showed that this difference is due to the
1018 friction on the back wall: at high friction, a pop-up develops in order to reduce sliding on the
1019 back wall, whereas at low friction we observe a single forward thrust and vertical slip on the
1020 back wall. Here, sands and sidewall materials are identical in all models, and all models
1021 develop the same initial structure: a pop-up. This is a substantial improvement compared to
1022 the previous comparison (Schreurs et al., 2006), and a confirmation that the pop-up / forward
1023 thrust discrepancy is due to differences in friction of sand against the back wall material,
1024 provided other parameters like basal friction are fixed.

1025
1026

1027 *6.2. Influence of experimental set-up on model reproducibility*

1028

1029 The results of our three different thrust experiments demonstrate that the set-up itself has an
1030 influence on model reproducibility with experiment 1 showing the highest degree of
1031 similarity, followed by experiment 3 and then by experiment 2.

1032

1033 All experiment 1 models show exactly the same evolution, i.e. stable sliding of a triangular
1034 sand wedge without significant internal deformation and a surface slope that remains nearly
1035 constant throughout the experiment. Experiments 2 and 3 consist of horizontally layered
1036 models that are shortened by inward movement of a mobile wall. The undeformed models in
1037 both experiments represent subcritical wedges. The only difference between the two
1038 experimental setups is the presence of a thin, rigid basal sheet attached to the mobile wall in
1039 experiment 3. Hence, in experiment 3 a singularity is stationary with respect to the moving
1040 sheet tip and displacement of the mobile wall forces deformation to remain localized at the
1041 singularity resulting in a good similarity among all models with only minor variations in
1042 quantitative parameters such as surface slope, and thrust dip. In contrast, in experiment 2, the
1043 singularity is located at the active forward thrust, which is less constrained in space, and
1044 consequently models show a larger variability, in particular with regard to the number of
1045 forward thrusts, which in experiment 2 varies from 2 to 9 for forward thrusts and from 1 to 9
1046 for backthrusts.

1047

1048

1049 *6.3. Variations within and between models*

1050

1051 Both experiments 2 and 3 models show similar cross-sectional evolutions demonstrating
1052 reproducibility of first-order experimental results. However, for both experiments we do
1053 observe variations of structures both in map view and in cross sections. Thrusts merge along
1054 strike and show slight variations in their surface strike. Quantification of parameters in cross-
1055 sections also documents variations among models and lateral variations within one model, in
1056 particular for experiment 2. Possible explanations for these variations are discussed below:

1057

1058 (1) Even though the prescribed model construction techniques were stringent concerning
1059 sieve mesh size, sifting height, and sifting rate, it is unlikely in practice that the initial
1060 undeformed model is perfectly homogeneous and has constant values of internal

1061 friction, basal friction, internal cohesion and basal cohesion throughout. Slight
1062 variations in these values might be caused by small changes in sifting height or sifting
1063 rate during model construction or might have occurred during off-scraping of excess
1064 material. An inspection of the first-formed pop-up structure in the centre of XRCT
1065 experiment 2 models shows that those of Bern 2B and IFP 2A are quite asymmetric,
1066 with a steep backthrust dipping at c. 45° and a relatively shallow forward thrust. The
1067 other three models (Bern 2A, GFZ@Bern, and IFP 2B) have a more symmetric pop-up
1068 structure. Analogue models testing the influence of basal friction on the thrust wedge
1069 shape (e.g. Colletta et al., 1991; Huiqi et al., 1992) reveal that initially horizontally
1070 layered models with a low basal friction have a more symmetric style of thrusting than
1071 models with a high basal friction, which have a more asymmetric thrust style. This
1072 would suggest a variability in initial basal friction between the models, at least near
1073 the moving wall with models Bern 2B and IFP 2A having higher values of basal
1074 friction. This variability, as well as the variability of the measured friction of sand on
1075 Alkor foil in ring-shear tests (boundary friction, Table 1), could be due to repeated use
1076 of the Alkor foil, which would thus change (probably increase) basal frictional
1077 properties during repeated tests, as sand grains scratch its surface. In our experiments
1078 electrostatic forces will occur at the interface Alkor foil / sand, but their magnitudes
1079 are difficult to determine and their effect on the structures remains unknown.
1080 Variability in model results might also be caused by the presence of tiny air pockets
1081 trapped below the Alkor foil during adhesion to the base of the sandbox resulting in a
1082 slightly uneven surface and varying basal friction conditions.

1083
1084 (2) During the initial stages of the experiment, shortening of the model will result in
1085 compaction of the sand grains close to the mobile wall, and hence compaction
1086 gradients will form. Adam et al. (2013) could visualize this diffuse, non-localised
1087 deformation in analogue models using digital image correlation techniques applied on
1088 XRCT images. The lateral variations in compaction might enhance or reduce the
1089 initial variations in mechanical properties introduced during model construction. The
1090 spatial and temporal evolution of the compaction gradients will depend on the
1091 experimental set-up. For experiments 1 and 2, initial compaction occurs adjacent to
1092 the mobile wall, whereas in experiment 3, it starts near the tip of the basal sheet.

1093

1094 (3) Laboratory climatic conditions varied and in particular the relative humidity might
1095 have an influence on the cohesion of the sands, and thus on model results. Forsyth et
1096 al. (2002) investigated the influence of atmospheric humidity on glass spheres with
1097 different sizes. For the range of grain size used in our experiments (c. 80-200 μm),
1098 Forsyth et al. (2002) could show that glass spheres only start to show cohesive or
1099 stick-slip behaviour at relative humidities $> 65\%$. As most laboratories reported
1100 humidities below 65%, humidity is probably not a major factor influencing model
1101 results. However, it has to be kept in mind that Forsyth et al. (2002) only investigated
1102 the influence of humidity on perfectly spherical grains with identical grain size. Our
1103 quartz and corundum sands have an angular grain shape and a heterogeneous grain
1104 size distribution, and an uncertainty remains with regard to the role of humidity on the
1105 cohesion of our material.

1106

1107 (4) One of the striking results of the present comparison is the large variability in surface
1108 slopes, thrust dips, and particularly numbers of thrusts. Large variations occur even
1109 between repetition of experiments in the same laboratory. They also do occur along
1110 strike of single models. Details of each thrust is little reproducible after substantial
1111 shortening, despite our present efforts to remove experimental imperfections. This
1112 variability is a feature of the localisation process in frictional materials that cannot be
1113 completely removed by an improvement of experimental protocols. The exact location
1114 and dip of a thrust depend on minute changes in the distribution of sand grains that
1115 promote or delay the onset of dilatation, which has a long term effect upon further
1116 shortening. This can also be understood theoretically by recalling the central argument
1117 of the critical taper theory: that the wedge will deform to maintain the stress field
1118 everywhere on the verge of Coulomb failure. Any model imperfection ruins this
1119 simplicity and triggers the next failure, resulting in a system that is highly sensitive to
1120 initial conditions and to external perturbations (Mary et al., 2013a).

1121

1122 *6.4. Recommendations and potential improvements*

1123

1124 We recommend that a minimum standard be adhered for experimental descriptions. Often
1125 analogue model materials are inadequately characterized and model building and
1126 experimental procedures are incomplete. Experimental descriptions should include the

1127 physical characteristics (e.g. grain size, grain size distribution, grain shape) of the analogue
1128 materials, the mechanical properties (e.g. cohesion and angles of internal friction at peak and
1129 stable strength, basal friction) and how measured, model construction technique (e.g.,
1130 physical handling technique, size of sieve mesh, sifting rate, scraping details) and laboratory
1131 climatic conditions (temperature, humidity).

1132

1133 In order to reduce the influence of the human factor and minimize initial heterogeneities in
1134 material properties introduced during model construction, one could consider using a special
1135 sedimentation device for sifting sands. Maillot (2013) built a sedimentation device in an
1136 attempt to produce uniform sand packs. For Fontainebleau sand with a 250 μm median grain
1137 size, Maillot (2013) could show that the density of the resulting sandpack is close to its
1138 maximum value, reproducible and uniform. Although the sedimentation device surely
1139 presents an advantage in terms of model homogeneity, it requires extensive testing to produce
1140 relatively level sand packs. Spatial variations in the thickness of the sand layers cannot be
1141 avoided due to downward air currents during infill resulting in a central depression and excess
1142 thickness near the four walls. Whereas thickness variations in the centre of the sandbox are
1143 mostly below 4% for a model thickness of c. 3 to 4 cm, variations near the lateral walls are
1144 more important (Maillot, 2013). Although a best value of +6% is reached, the excess
1145 thickness near the walls can be larger than 100% depending on the type of sand, the
1146 sedimentation flux and the number of sieves used (Maillot, 2013). In any case, the sieving
1147 process is a central ingredient in model construction. Other devices could be developed for
1148 special setups or for producing layered models consisting of different granular materials.

1149 Cubas et al. (2010) performed analogue model experiments using such a sedimentation device
1150 to quantify the intrinsic variability of model results. The experiments consisted of shortening
1151 an initially subcritical sand wedge resting on a flat sand layer by translating the wall on the
1152 wedge side over a distance of 30 mm. By repeating experiments and applying statistical
1153 methods to observables measured in final-state cross sections through the central part of the
1154 box (where side-wall effects did not play a role), they could for example show that the error
1155 bar for fault dips are c. 3.3° for the first pop-up that forms, with forward thrusts dipping at 38°
1156 $\pm 3.2^\circ$ and backthrusts at $41 \pm 3.3^\circ$. These values are of course dependent on the granular
1157 material used, the experimental protocol and the set-up. Although our experiments 2 and 3
1158 consisted of a different set-up (our models are initially horizontal), used different granular
1159 materials and did not involve the sedimentation device of Maillot (2013), a comparison of the

1160 error bars for fault dips of forward and backthrusts measured at the top in XRCT sections
1161 through the centre of the model shows largely comparable error bars, with forward thrusts
1162 dipping at $29 \pm 3^\circ$ in both experiments 2 and 3. Backthrusts in experiment 2 have a larger
1163 error bar with faults dipping at $36 \pm 9^\circ$, whereas backthrusts in experiment 3 show a smaller
1164 error bar with faults dipping at $30 \pm 2^\circ$.

1165

1166 Compaction of the granular model material prior to deformation might also reduce variability
1167 in model results. Compaction, however, would need to be done in a systematic and
1168 reproducible way, e.g. by shaking or tapping. In addition, one would need to determine the
1169 mechanical properties of compacted granular material using an apparatus in which
1170 compaction is achieved in an identical way as for the analogue model.

1171

1172 In our model comparison we choose to use quartz and corundum sand used at the laboratory
1173 in Bern. These sands have their own specific physical characteristics and mechanical
1174 properties. It can not be excluded that the use of another type of sand, with different grain
1175 shape, grain size, and grain size distribution, might improve experimental reproducibility.
1176 This would require further testing.

1177

1178 Finally, repeating experiments should be performed in order to ensure that intrinsic variability
1179 (in identical setups) is properly defined and smaller than the expected effects related to
1180 (extrinsic) “controlling” factors.

1181

1182

1183 **7. Concluding remarks**

1184

1185 We have made a quantitative comparison of brittle thrust experiments to evaluate the
1186 variability among analogue models and to appraise reproducibility and limits of model
1187 interpretation. The reasons for variability in analogue model experiments boils down to the
1188 system-wide effectiveness of small disturbances. Bearing this in mind the philosophy behind
1189 our benchmark was to minimize this by choosing the most simple and most insensitive setups,
1190 boundary conditions and materials keeping them as homogeneous as possible in the different
1191 laboratories. For three different thrust wedge experiments, we quantified parameters such as
1192 fault dip, fault spacing, thrust number, thrust formation and surface slope. In contrast to the
1193 model comparison of Schreurs et al. (2006) we made quantitative comparisons of model

1194 results in sections at least 5 cm away from the sidewalls, to avoid non-representative results
1195 due to complex interactions between sidewall friction and basal friction.

1196

1197 Our model comparison suggests that one of the sources of experimental variability is related
1198 to slight variations in how material is deposited in the sandbox and how scraping of material
1199 occurred to flatten the surface. Small changes in sifting height, sifting rate, and scraping will
1200 result in slightly heterogeneous material densities, which will affect the mechanical properties
1201 of the granular material, and result in lateral and vertical differences in peak and basal friction
1202 angles, as well as cohesion values once the model is constructed. Initial variations in basal
1203 friction are most likely responsible for most of the variability in model results. Part of the
1204 variability might also be explained by our choice not to compact models prior to deformation.
1205 In our benchmark, shortening causes compaction of the granular materials leading to
1206 compaction gradients that are superposed on previous heterogeneities introduced during
1207 model construction. Differences in relative humidity between participating laboratories might
1208 also have an effect on granular material cohesion and hence on model variability. The
1209 influence of humidity on the cohesion of the sands used in our model comparison remains
1210 poorly known. Taking into account the experimental studies of Forsyth et al. (2002), however,
1211 we consider that its influence on model variability is most likely minimal.

1212

1213 Our observations highlight the limits of up-scaling quantitative analogue model results to
1214 nature or for making comparisons with numerical models (Buiter et al., 2016). It will remain
1215 difficult to scale quantitative results such as number of thrusts, spacing between forward
1216 thrusts, or width of pop-up structures from model to nature. The way forward is perhaps to
1217 build statistical descriptions of the measured parameters rather than using single values. These
1218 would in turn provide more reliable data for a comparison to numerical simulations.

1219

1220 Our model comparison shows that even for simple plane-strain experiments with prescribed
1221 stringent model construction techniques, the human factor plays a decisive role, and even
1222 when one modeler repeats the experiment, the quantitative model results show considerable
1223 variability. Although this might at first seem a discouraging conclusion, the failure of the
1224 models to achieve perfect replicability despite our precautions can be considered a success in
1225 documenting the importance of initial model heterogeneity. As is the case for natural thrust
1226 wedges, the initial undeformed sand model is not perfectly homogeneous throughout, but
1227 already has slight variations in mechanical properties such as internal friction, basal friction,

1228 internal cohesion and basal cohesion. Small differences in these parameters will affect how,
1229 where and when the first thrusts form and will affect the details of the timing and location of
1230 subsequent thrusts.

1231
1232 The variability reported in our benchmark is considerable and should serve the analogue
1233 modeling community as a constraint on the best expected “precision” of models. We can
1234 assume that as model setups become more complex (e.g. by introducing detachment layers,
1235 erosion, sedimentation, lateral and vertical changes in material geometry, etc.) the “precision”
1236 will drop drastically. We hope that this benchmark serves to sensitize the community and
1237 helps to prevent over-interpretation of analogue models especially in view of recent
1238 developments that allow quantitative measurements to be made easily at high precision using
1239 laser scanning or image correlation techniques.

1240

1241

1242 **Acknowledgments**

1243

1244 This study was supported by SNF Grant 200020-109320, 200020-122143 and 200021-140608
1245 (Guido Schreurs), Discovery and Equipment grants from the Natural Sciences and
1246 Engineering Research Council of Canada, NSERC (Alexander Cruden), the Fundação de
1247 Amparo à Pesquisa do Estado de Minas Gerais (Fapemig), CRA 871/06 (Caroline J.S.
1248 Gomes), and the Swedish Research Council, Grant 2008-3443 (Faramarz Nilfouroushan) .

1249

1250

1251 **References**

1252

1253 Adam, J., Urai, J.L., Wieneke, B., Oncken, O., Pfeiffer, K., Kukowski, N., Lohrmann, J.,
1254 Hoth, S., van der Zee, W., Schmatz, J., 2005. Shear localisation and strain distribution
1255 during tectonic faulting - new insights from granular-flow experiments and high-
1256 resolution optical image correlation techniques. *Journal of Structural Geology* 27, 283-
1257 301.

1258 Adam, J., Klinkmüller, M., Schreurs, G., Wieneke, B., 2013. Quantitative 3D strain analysis
1259 in analogue experiments simulating tectonic deformation: Integration of X-ray computed
1260 tomography and digital volume correlation techniques. *Journal of Structural Geology*, 55,
1261 127-149.

- 1262 Bernard, S., Avouac, J.-P., Dominguez, S., Simoes, M., 2007. Kinematics of fault-related
1263 folding derived from a sandbox experiment. *Journal of Geophysical Research* 112, J
1264 B03S12, doi:10.1029/2005JB004149.
- 1265 Buitter, S.J.H., 2012. A review of brittle compressional wedge models. *Tectonophysics* 530-
1266 531, 1-17, doi: 10.1016/j.tecto.2011.12.018..
- 1267 Buitter, S.J.H., Schreurs, G., Albertz, M., Gerya, T.V., Kaus, B., Landry, W., Le Pourhiet, L.,
1268 Mishin, Y., Egholm, D.L., Cooke, M., Maillot, B., Thieulot, C., Crook, T., May, D.,
1269 Souloumiac, P., and Beaumont, C., 2016. Benchmarking numerical models of brittle
1270 thrust wedges. *Journal of Structural Geology*, <http://dx.doi.org/10.1016/j.jsg.2016.03.003>
- 1271 Colletta, B., Bale, P., Ballard, J.F., Letouzey, J., Pinedo, R., 1991. Computerized Y-ray
1272 tomography analysis of sandbox models: examples of thin-skinned thrust systems.
1273 *Geology* 19, 1063-1067.
- 1274 Costa, E., Vendeville, B., 2004. Experimental insights on the geometry and kinematics of
1275 fold-and-thrust belts above weak, viscous evaporitic décollement: reply to comments by
1276 Hemin Koyi and James Cotton. *Journal of Structural Geology* 26, 2139-2143.
- 1277 Cubas, N., Maillot, B., Barnes, C., 2010. Statistical analysis of an experimental compressional
1278 sand wedge. *Journal of Structural Geology* 32, 818-831.
- 1279 Dahlen, F.A., Suppe, J., 1988. Mechanics, growth, and erosion of mountain belts. *Geological*
1280 *Society of America, Special Paper* 218, 161-178.
- 1281 Dahlen, F.A., Suppe J., Davis, D., 1984. Mechanics of fold-and-thrust belts and accretionary
1282 wedges: cohesive Coulomb theory. *Journal of Geophysical Research* 89, 10087-10101.
- 1283 Forsyth, A.J., Hutton, S., Rhodes, M.J., 2002. Effect of cohesive interparticle force on the
1284 flow characteristics of granular materials. *Powder Technology* 126, 150-154.
- 1285 Gomes, C.J.S., 2013. Investigating new materials in the context of analog-physical models.
1286 *Journal of Structural Geology* 46, 158-166.
- 1287 Huiqi, L., McClay, K.R., Powell, D., 1992. Physical models of thrust wedges. In: McClay,
1288 K.R. (Ed.), *Thrust Tectonics*, Chapman & Hall, London, 71-81.
- 1289 Krantz, RW., 1991. Measurements of friction coefficients and cohesion for faulting and fault
1290 reactivation in laboratory models using sand and sand mixtures. *Tectonophysics* 202,
1291 319-333.
- 1292 Lohrmann, J., Kukowski, N., Adam, J., Oncken, O., 2003. The impact of analogue material
1293 properties on the geometry, kinematics, and dynamics of convergent sand wedges.
1294 *Journal of Structural Geology* 25, 1691-1711.

1295 Maillot, B., 2013. A sedimentation device to produce uniform sand packs. *Tectonophysics*
1296 593, 85-94.

1297 Mary B.C., Maillot, B., Leroy, Y.M. 2013a. Deterministic chaos in frictional wedges revealed
1298 by convergence analysis, *International Journal for Numerical and Analytical Methods in*
1299 *Geomechanics*, doi: 10.100/nag.2177.

1300 Mary B.C., Maillot, B., Leroy, Y.M., 2013b. Predicting orogenic wedge styles as a function
1301 of analogue erosion law and material softening, *Geochemistry, Geophysics, Geosystems*
1302 14, doi:10.1002/ggge.20262.

1303 Panien, M., Schreurs, G., Pfiffner, O.A., 2006. Mechanical behaviour of granular materials
1304 used in analogue modeling: insights from grain characterisation, ring-shear tests and
1305 sandbox tests. *Journal of Structural Geology* 28, 1710-1724, doi:
1306 10.1016/j.tecto.2011.06.022.

1307 Rosenau, M., Lohrmann, J., Oncken, O., 2009. Shocks in a box: An analogue model of
1308 subduction earthquake cycles with application to seismotectonic forearc evolution.
1309 *Journal of Geophysical Research* 114, B1, DOI: 10.1029/2008JB005665.

1310 Schellart, W.P., 2000. Shear test results for cohesion and friction coefficients for different
1311 granular materials: scaling implications for their usage in analogue modeling.
1312 *Tectonophysics* 324, 1-16.

1313 Schreurs, G., Buiter, S.J.H., Boutelier, D., Corti, G., Costa, E., Cruden, A., Daniel, J.-M.,
1314 Hoth, S., Koyi, H., Kukowski, N., Lohrmann, J., Ravaglia, A., Schlische, R.W.,
1315 Withjack, M.O., Yamada, Y., Cavozi, C., DelVentisetti, C., Elder Brady, J.A.,
1316 Hoffmann-Rother, A., Mengus, J.-M., Montanari, D., Nilforoushan, F., 2006. Analogue
1317 benchmarks of shortening and extension experiments. In: Buiter, S.J.H. and Schreurs, G.
1318 (Eds), *Analogue and Numerical Modeling of Crustal-Scale Processes*. Geological
1319 Society, London, Special Publications 253, 1-25.

1320 Schulze, D., 2008. *Pulver und Schüttgüter – Fliesseigenschaften und Handhabung*, Springer,
1321 Berlin.

1322 Stockmal, G.S., CBeaumont, C., Nguyen, M., Lee, B., 2007. Mechanics of thin-skinned fold-
1323 and-thrust belts: Insights from numerical models. *Geological Society of America Special*
1324 *Paper* 433, 63-98.

1325 Souloumiac P., Krabbenhoft, K., Leroy, Y.M., B. Maillot, B., 2010. Failure in accretionary
1326 wedges with the maximum strength theorem: numerical algorithm and 2D validation,
1327 *Computational Geosciences*, doi:10.1007/s10596-010-9184-4.

- 1328 Souloumiac, P., Maillot, B., Leroy, Y. M., 2012. Bias due to side wall friction in sand box
1329 experiments. *Journal of Structural Geology* 35, 90-101.
- 1330 Zhao, W.-L., Davis, D.M., Dahlen, F.A., Suppe, J., 1986. Origin of convex accretionary
1331 wedges: evidence from Barbados. *Journal of Geophysical Research* 91, 10246-10258.
- 1332
- 1333
- 1334

1335
1336
1337
1338
1339
1340
1341
1342
1343
1344
1345
1346
1347
1348
1349
1350
1351
1352
1353
1354
1355
1356
1357
1358
1359
1360
1361
1362
1363
1364
1365
1366
1367
1368

Fig. 1. Experimental set-up used in model comparison experiments by Schreurs et al., (2006). Model consists of a 3.5 cm-thick sand layer with an embedded microbeads layer and an overlying sand wedge with a surface slope of 10° adjacent to the mobile wall. All walls are covered by Alkor foil. Figure reproduced from Schreurs et al. (2006) with permission from the Geological Society of London.

Fig. 2. Model comparison showing cross sections through thrust wedge after 2, 6 and 14 cm of shortening. The experimental set-up is shown in Fig. 1. The sections of Bern and IFP Rueil Malmaison are X-ray computer tomography (XRCT) images through the center of the model, whereas the remaining sections are sidewall observations. Microbeads layer indicated by “m”. Figure modified after and reproduced from Schreurs et al. (2006) with permission from the Geological Society of London.

Fig. 3. Physical characteristics of the quartz and corundum sand used in the experiments (modified after Panien et al., 2006). Upper and lowermost images are photographs and SEM images, respectively. Width of each SEM image is $1740 \mu\text{m}$.

Fig. 4. Shear stress plotted versus shear strain for quartz sand (modified from Lohrmann et al., 2003; Panien et al., 2006). Strain softening from peak strength to stable strength correlates with dilation of sand.

Fig. 5. Zoom of critical taper curves for cohesionless sand at peak strength ($\phi_p = 36^\circ$, $\phi_b = 15^\circ$ and $C = 0 \text{ Pa}$), cohesionless sand at stable strength ($\phi_s = 31^\circ$, $\phi_b = 15^\circ$ and $C = 0 \text{ Pa}$), and a cohesive sand at peak strength with depth-dependent cohesion ($\phi_p = 36^\circ$, $\phi_b = 15^\circ$ and $C = 20 \text{ Pa cm}^{-1}$ times z , with $z =$ depth, following Zhao et al. (1986)).

Fig. 6. Schematic illustration of measurements of a) surface slope, b) forward thrust spacing, and c) thrust dip angles. Surface slope is measured as the best fitting line through the valleys (Stockmal et al., 2007) and can only be determined once at least 2 thrusts have formed. Thrust spacing is measured horizontally from a newly initiated in-sequence forward thrust to the previously formed forward thrust.

1369 Fig. 7. Top view photograph illustrating position of cross sections at 25% (1), 50%-2 cm (2), 50% (3),
1370 50% + 2 cm (4), and 75% (5) of model width (measured parallel to mobile wall, which moves here
1371 from bottom to top). Model width is 80 cm in this particular experiment.

1372

1373 Fig. 8. Model set-up for experiment 1.

1374

1375 Fig. 9. Model building procedure for experiment 1 shown in cross section. A template with the shape
1376 of the final wedge is attached on top of each sidewall to guide the scraper (see Appendix A-2).
1377 Stippled line indicates sand wedge before final scraping.

1378

1379 Fig. 10. Evolution of experiment 1 model run at Bern after 0, 2 and 4 cm of shortening (a) XRCT
1380 sections through centre of model, (b) top view photographs of model.

1381

1382 Fig. 11. Cross sections through centre of experiment 1 models after 4 cm of shortening. Sections of
1383 Bern, GFZ@Bern, and IFP are XRCT images

1384

1385 Fig. 12. Model set-up for experiment 2.

1386

1387 Fig. 13. Cross-sectional evolution through centre of experiment 2 models after 1, 2, 6 and 10 cm of
1388 shortening as observed in XRCT images.

1389

1390 Fig. 14. Quantitative comparison of experiment 2 models analysed by XRCT. (a) Amount of
1391 shortening at which a forward thrust forms at centre of model. (b) Spacing to previously formed
1392 forward thrust at the moment of initiation of a new, in-sequence forward thrust.

1393

1394 Fig. 15. Dip angles of successive in-sequence forward (a) and back thrusts (b) in centre of experiment
1395 2 XRCT models, measured at top, middle and bottom.

1396

1397 Fig. 16. Surface slope evolution at centre of experiment 2 XRCT models. Only values that could be
1398 reliably measured in XRCT images are given.

1399

1400 Fig. 17. Cross sections through centre of experiment 2 models after 10 cm of shortening. Width of
1401 each panel shown is 25 cm. Note that some labs added a layer of sand before cutting the model. Cross
1402 sections from Lille 2A and 2B are at 50%-2cm position. Image quality of cross sections from Stanford
1403 2A and 2B was not good enough for reproduction.

1404

1405

1406 Fig. 18. Top views of experiment 2 models after 10 cm of shortening showing along-strike structural
1407 variability. Movement of mobile wall is from bottom to top Note that Lille 2A and 2B models have a
1408 grid of corundum sand imprinted on the surface, whereas Mexico 2A and 2B models used prescribed
1409 sand mixed with dark sand particles. All photos are shown at the same scale, given in the top left
1410 photo.

1411
1412 Fig. 19. Cross sections after 10 cm shortening for experiment 2 models at positions 25%, 50%-2 cm,
1413 50%, 50%+2 cm and 75% (see Fig. 6) showing along-strike structural variability. Note that some
1414 laboratories added a post-kinematic sand layer before wetting and sectioning.

1415
1416 Fig. 20. Surface slope after 10 cm of shortening at 25%, 50% and 75% positions for experiment 2
1417 models. The surface slope could not be reliably measured on all cross-sectional images. Surface slopes
1418 for Lille 2A and Lille 2B models were measured at 50%-2cm position. Numbers above symbols
1419 indicate difference between maximum and minimum slope angle within one particular model and are
1420 only given for those models in which the surface slope could be determined at all three positions.
1421 Surface slope values along one sidewall (0% position) are given for comparison and are generally
1422 higher.

1423
1424 Fig. 21. Number of forward and back thrusts at 25%, 50% and 75% position after 10 cm of shortening
1425 for experiment 2 models. Numbers above symbols indicate along-strike differences in number of
1426 thrusts and are only given for those models, in which thrusts could be reliably determined at all three
1427 positions.

1428
1429 Fig. 22. Model setup for experiment 3.

1430
1431 Fig. 23. Cross sections at 1, 2, 6 and 10 cm for all experiment 3 models analysed by XRCT.

1432
1433 Fig. 24. Dip of successive forward thrusts at time of initiation through centre of model, measured at
1434 bottom, middle and top in experiment 3 XRCT models.

1435
1436 Fig. 25. Evolution of surface slope through centre of experiment 3 XRCT models. The lines
1437 connecting measurements illustrate the oscillating behaviour of the surface slope, which tends to
1438 become less with increasing shortening. Numbers above symbols indicate the difference in maximum
1439 and minimum surface slope between the five models at a specific shortening increment.

1440
1441 Fig. 26. Cross sections after 10 cm of shortening through centre of experiment 3 models. Cross section
1442 of Stanford 3A is not shown, because image quality was insufficient for reproduction.

1443
1444 Fig. 27. Top views after 10 cm of shortening for experiment 3 models. Lille model has a surface grid
1445 of corundum sand.

1446
1447 Fig. 28. Cross sections after 10 cm shortening for experiment 3 models at positions 25%, 50%-2 cm,
1448 50%, 50%+2 cm and 75% of model width (see Fig. 7).

1449
1450 Fig. 29. Surface slope after 10 cm of shortening at 25%, 50% and 75% position for experiment 3
1451 models

1452
1453 Fig. 30. Number of forward thrusts after 10 cm of shortening at 25%, 50% and 75% position for
1454 experimental 3 models. Note that only those thrusts were considered that produced a noticeable offset
1455 at the surface. The number of thrusts in Stanford 3A and 3B models could not be reliably determined
1456 due to poor image quality.

1457
1458 Appendix A: Model construction techniques
1459 Appendix A-1: Mesh sieve
1460 Appendix A-2: Scraper to remove excess sand

1461
1462
1463
1464
1465 *Table 1. Range of mechanical properties of quartz and corundum sand obtained with a ring-shear tester. Values*
1466 *are rounded to nearest degree for friction angles and to nearest whole number for cohesion. n is number of ring-*
1467 *shear tests at normal stresses ranging from c. 500 to 2240 Pa.*

1468
1469 *Table 2. Overview of laboratory climatic conditions and model widths. Most laboratories performed experiments*
1470 *2 and 3 twice, and range of values for room temperature and relative humidity are indicated. Exceptions to the*
1471 *prescribed modeling procedure are also given.*

1472
1473

Shortening experiment - Mobile back wall

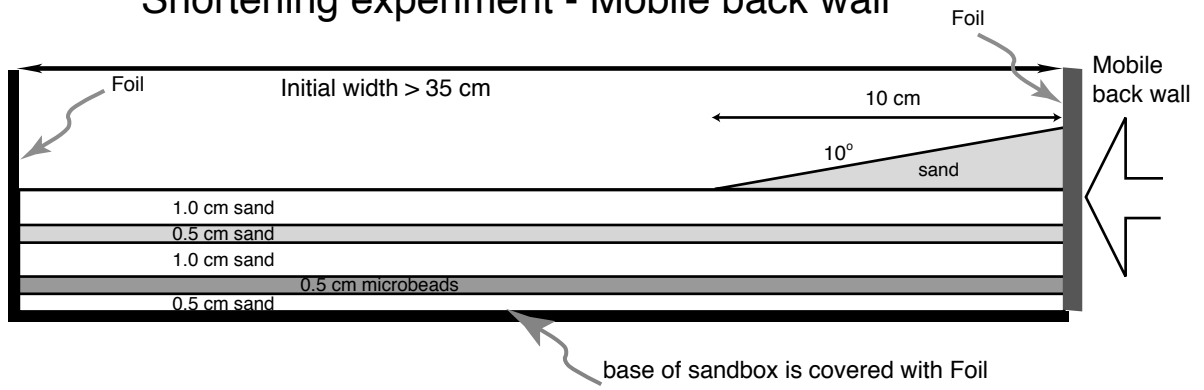
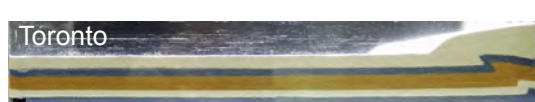
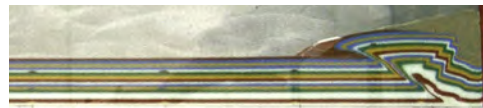
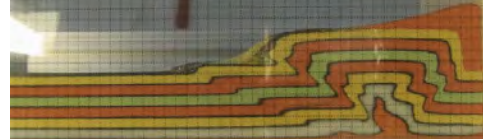
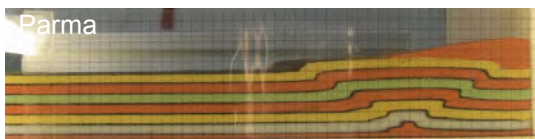
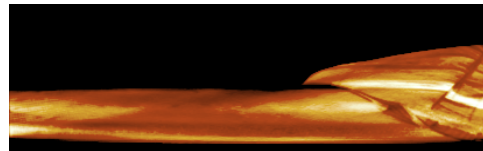
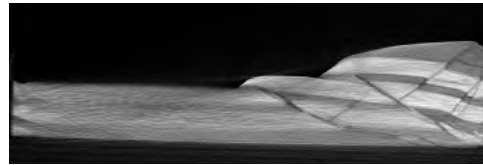
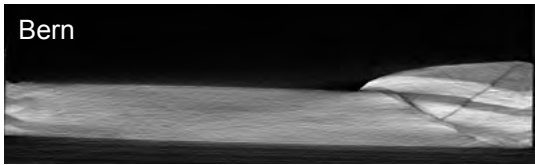


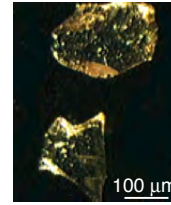
Fig. 1



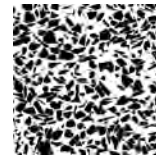
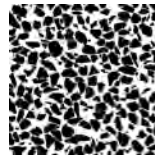
Quartz sand

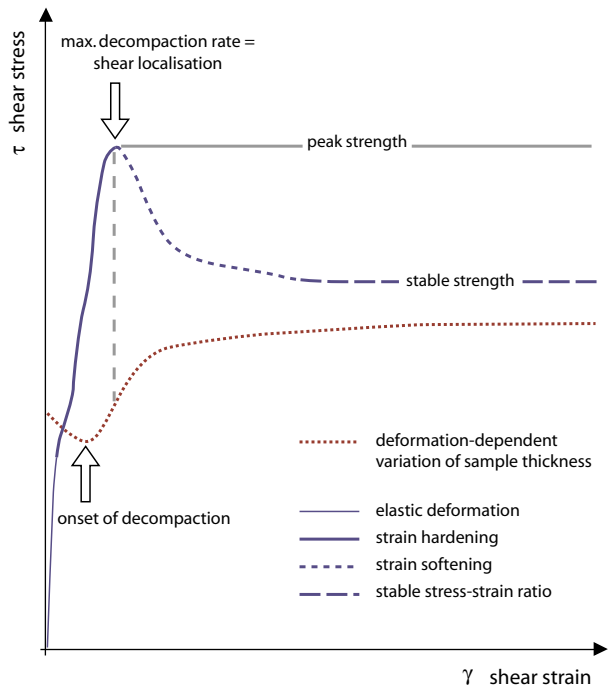


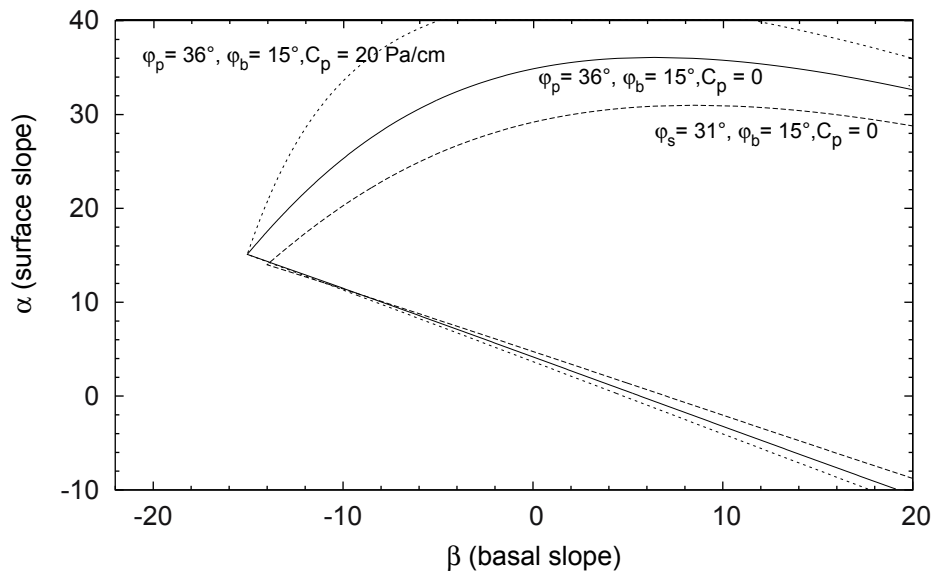
Corundum sand



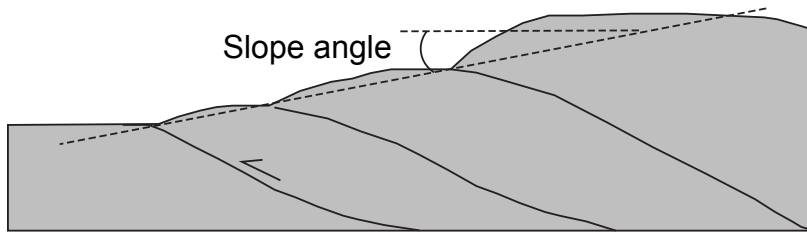
origin:	Triassic quartz sand	bauxite	
composition:	99 % SiO ₂	95 % Al ₂ O ₃	
grain size range (as indicated by supplier)	80-200 μm	88-125 μm	
grain size distribution (μm)			
bulk density:	sieved	1.56 g/cm ³	1.89 g/cm ³
	poured	1.32 g/cm ³	1.55 g/cm ³
porosity:	sieved	41.8 %	53.0 %
	poured	50.7 %	61.7 %
grain shape: texture	irregular surfaces	conchoidal fractures	
roundness	angular	very angular	



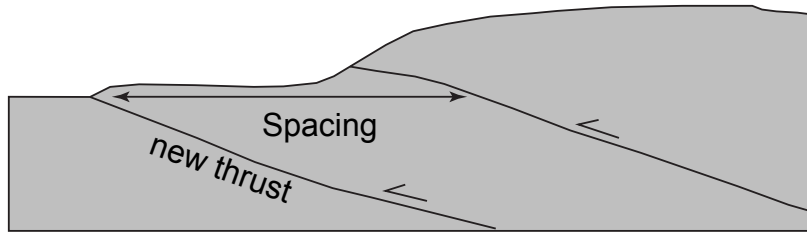




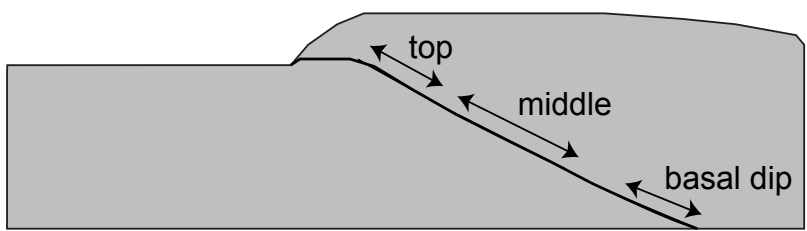
Surface slope



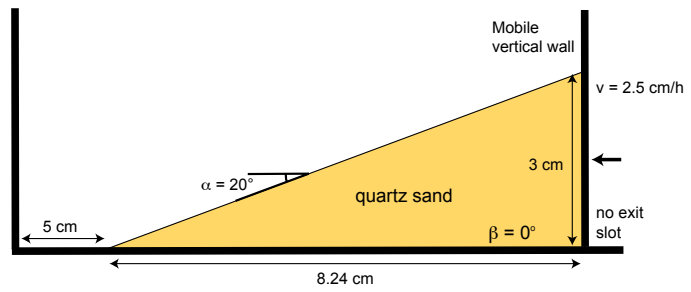
Thrust spacing



Thrust dip angle

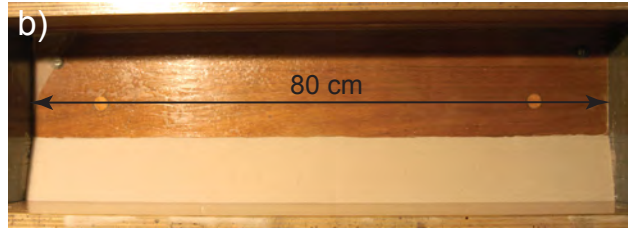








0 cm

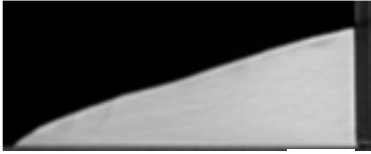


2 cm



4 cm





Bern



Cergy-Pontoise



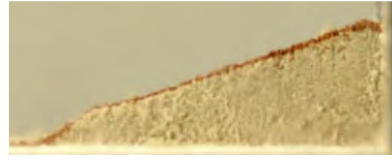
GFZ@Bern



IFP



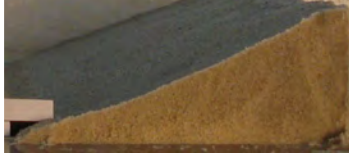
Kyoto



Melbourne



Mexico



Ouro Preto



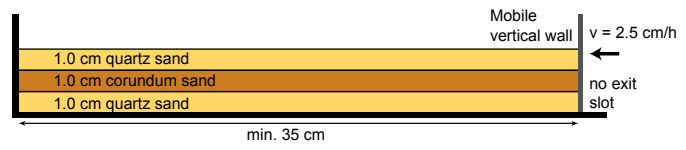
Piscataway

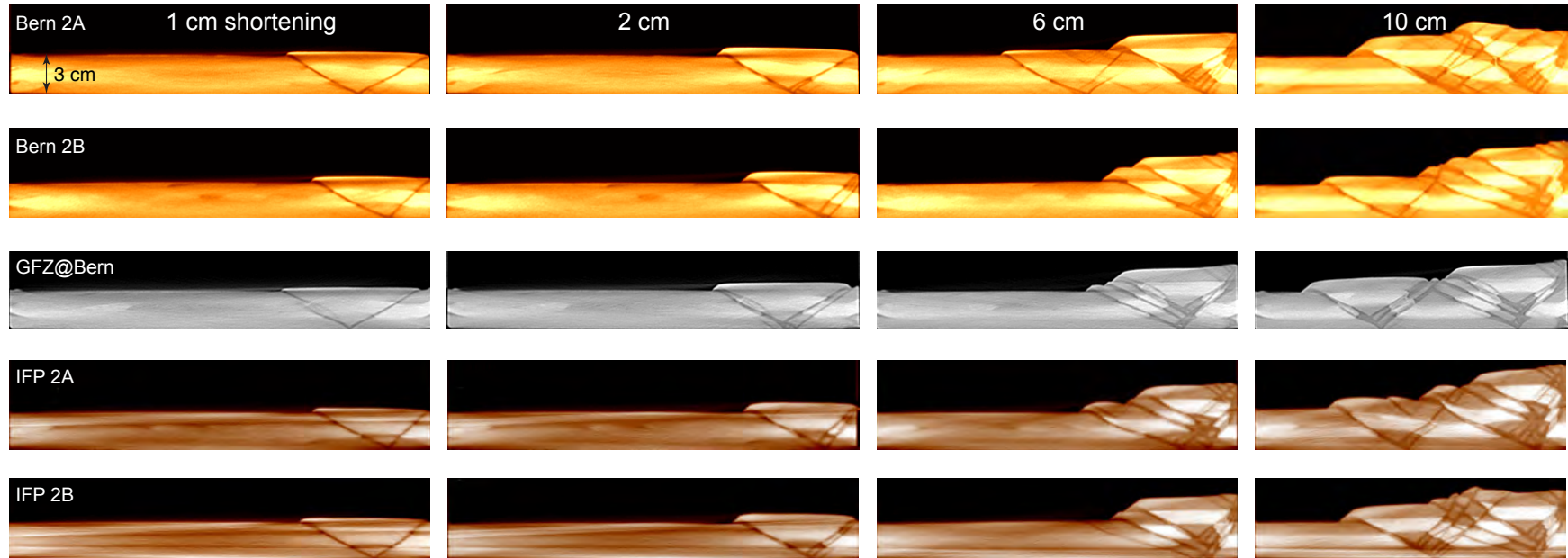


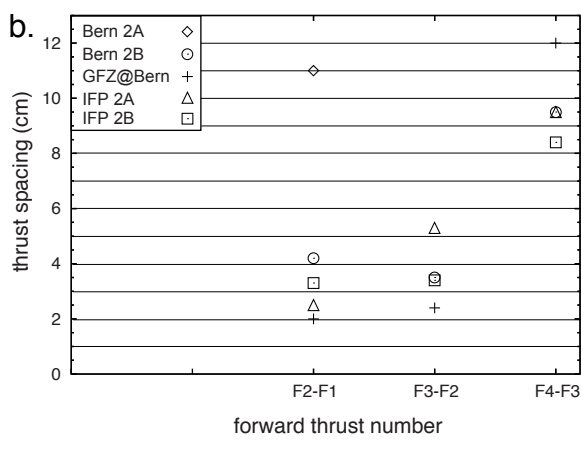
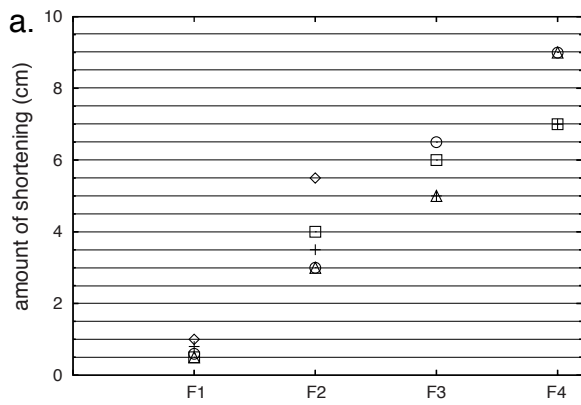
Toronto

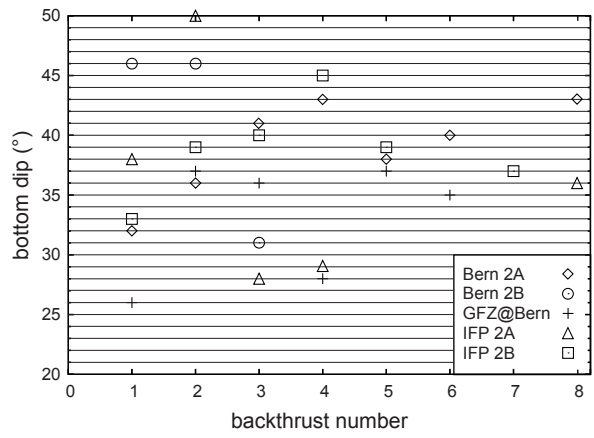
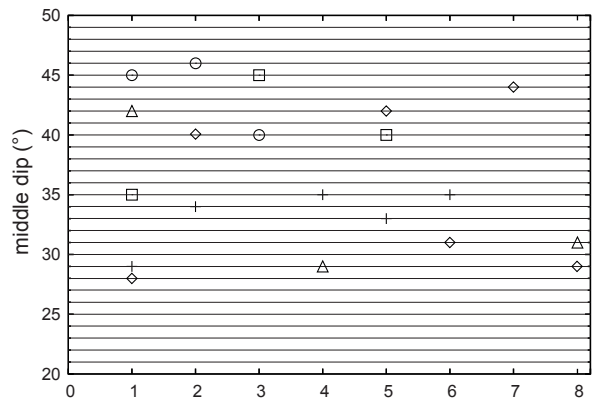
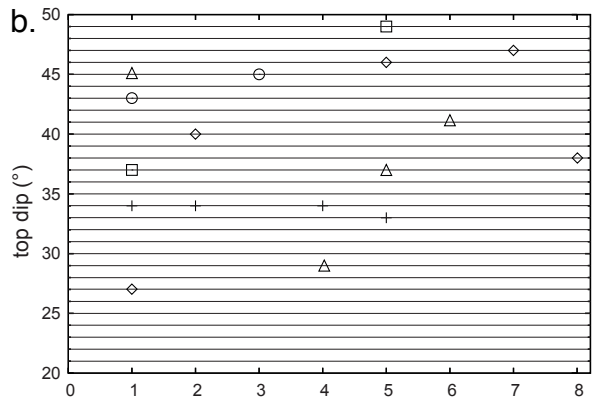
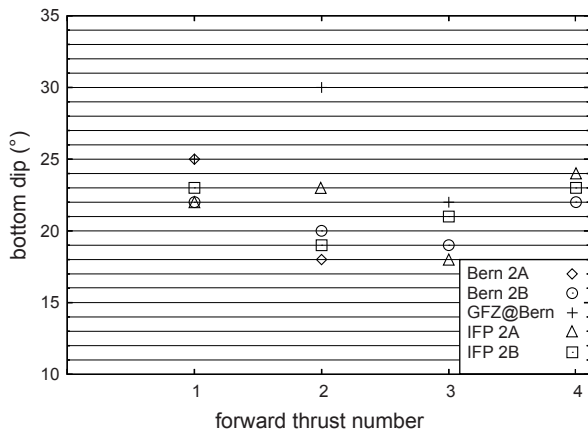
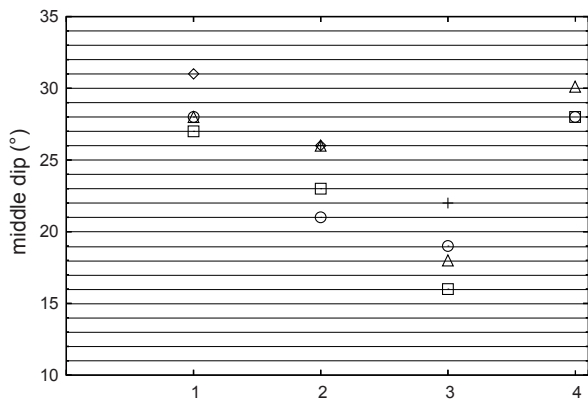
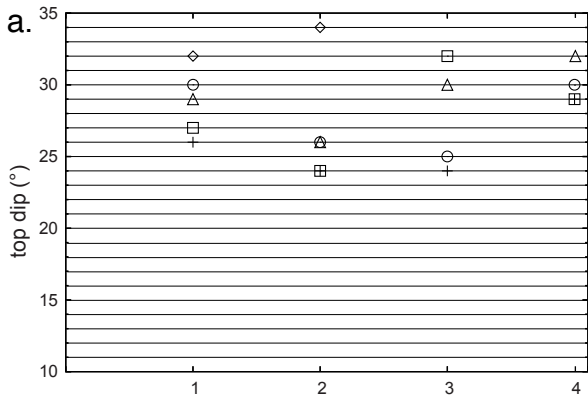


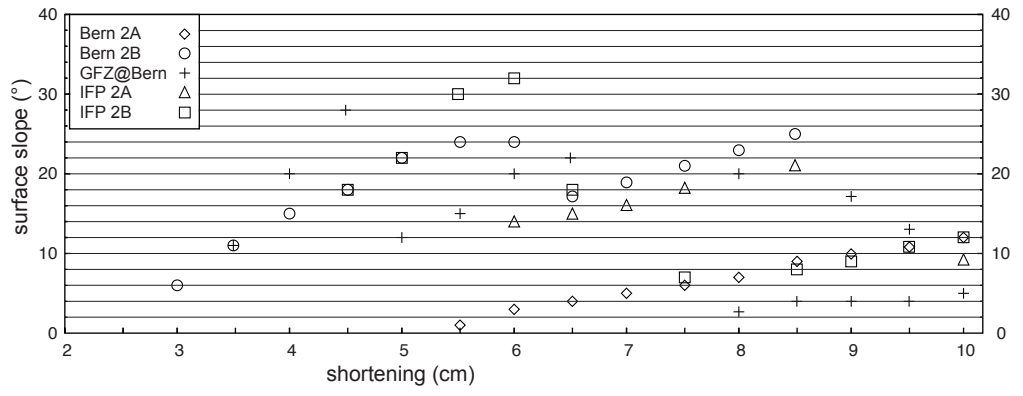
Uppsala

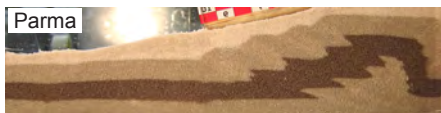
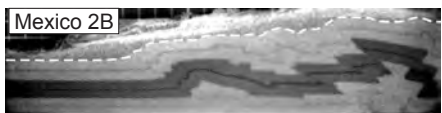
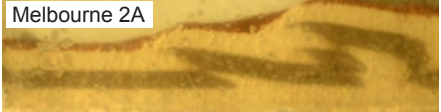
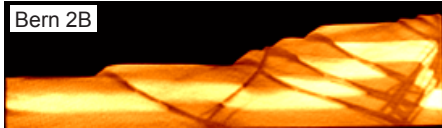


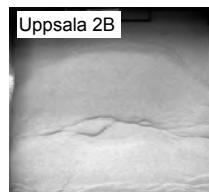
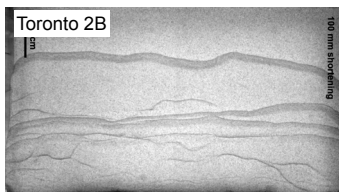
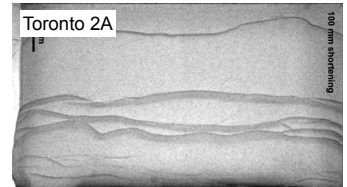
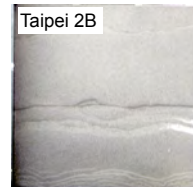
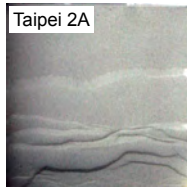
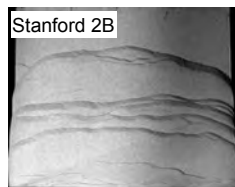
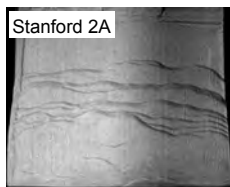
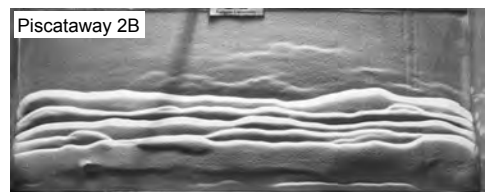
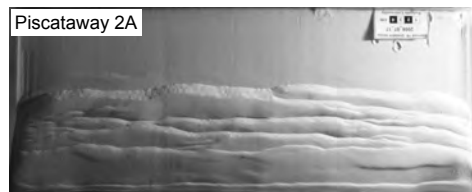
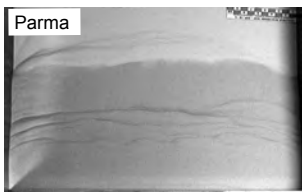
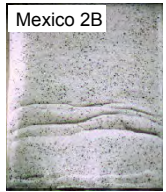
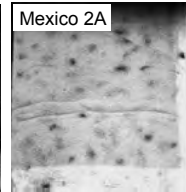
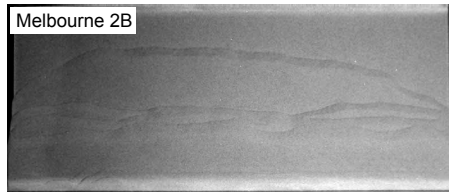
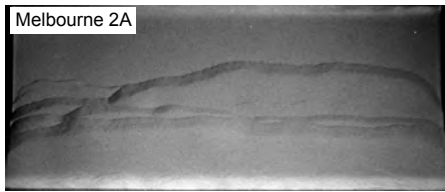
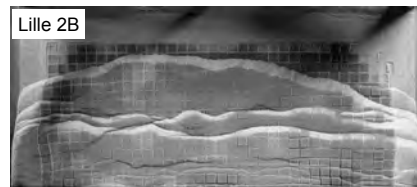
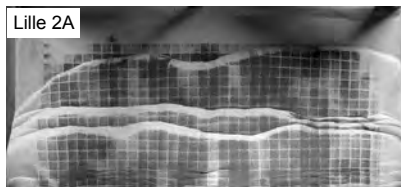
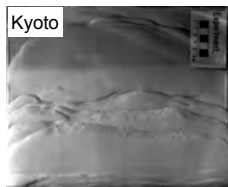
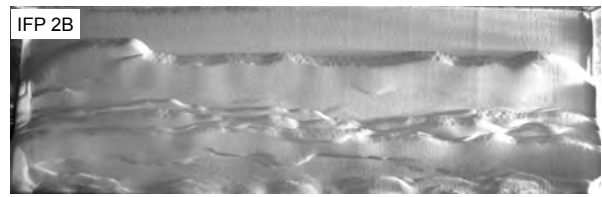
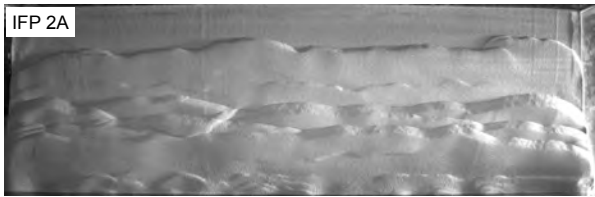
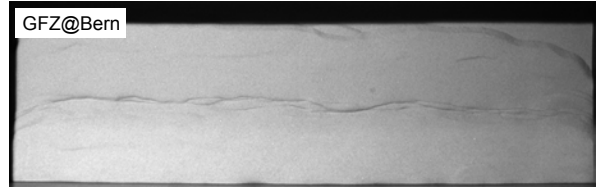
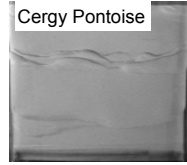
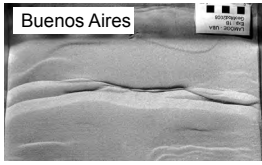
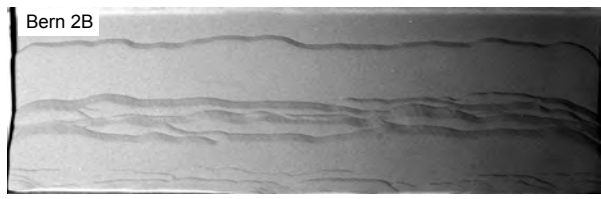
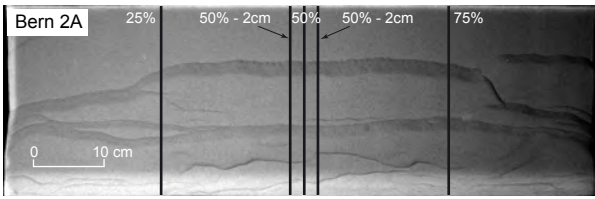


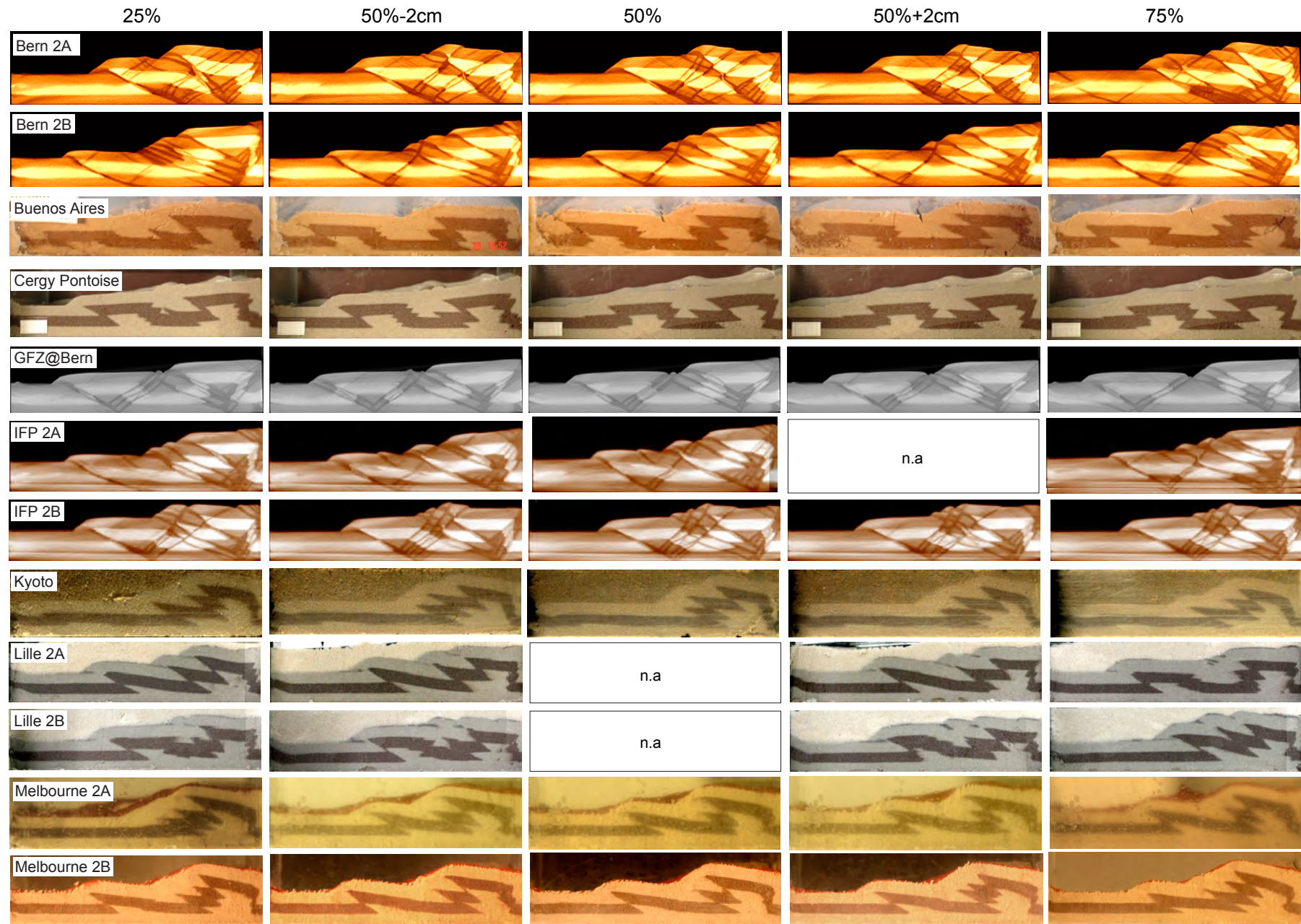












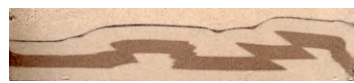
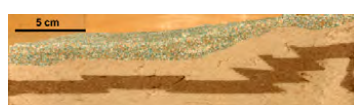
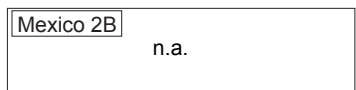
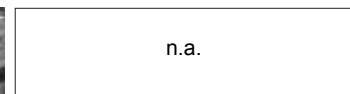
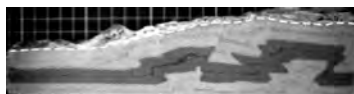
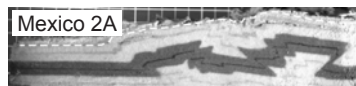
25%

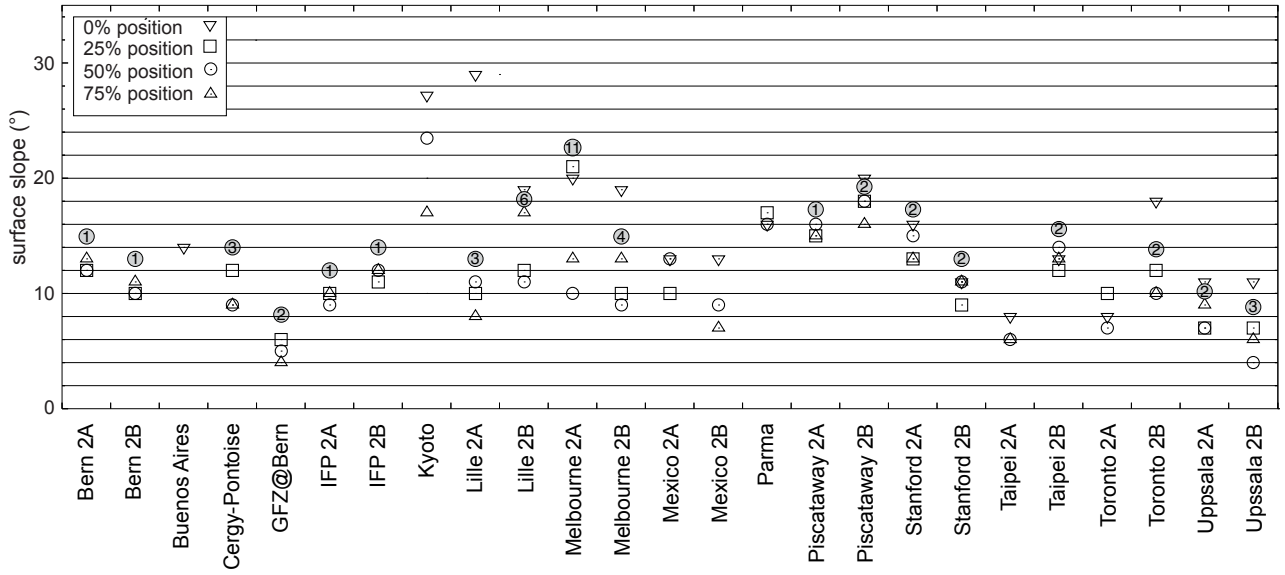
50%-2cm

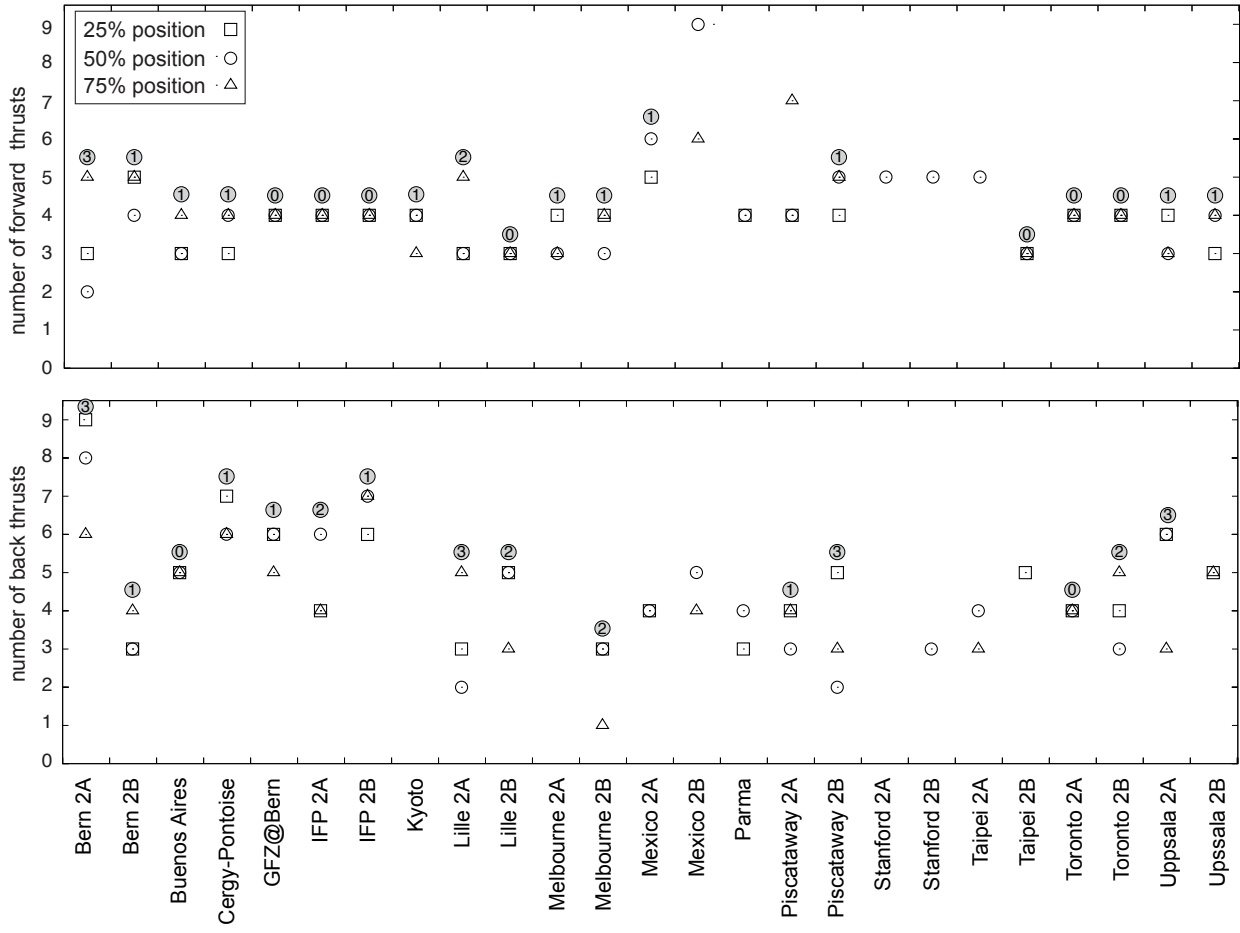
50%

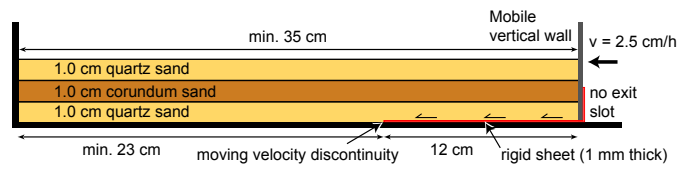
50%+2cm

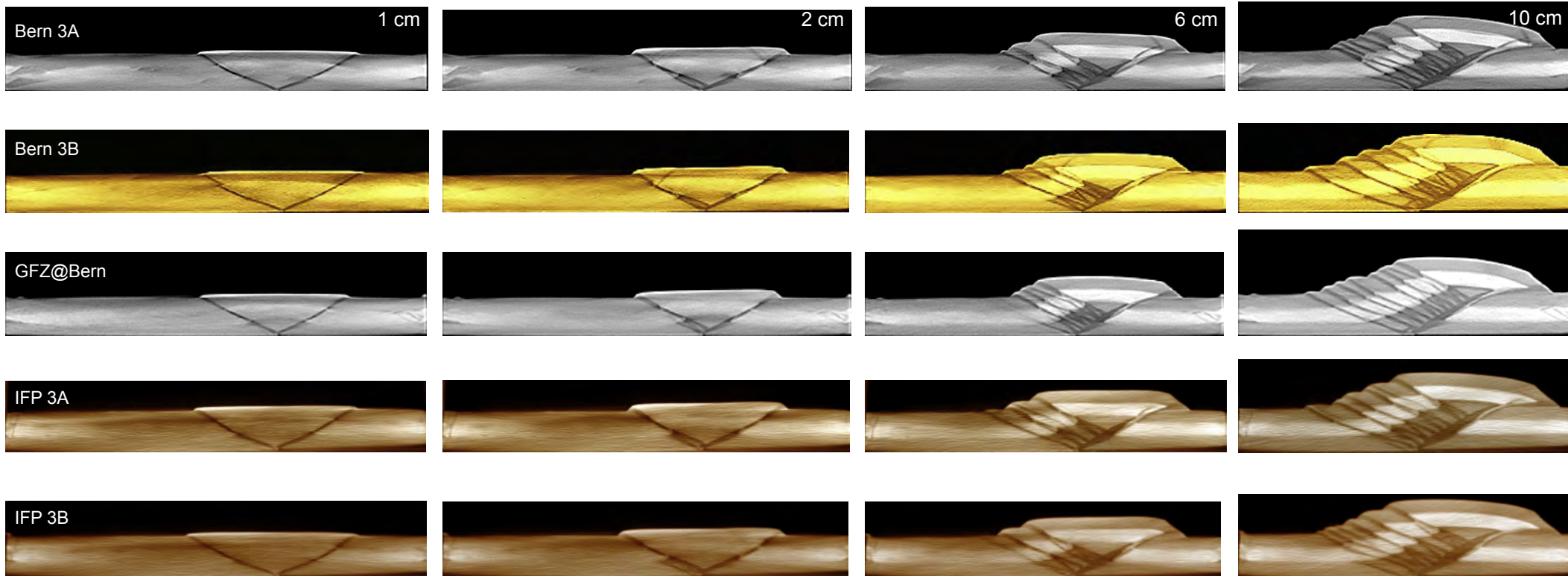
75%

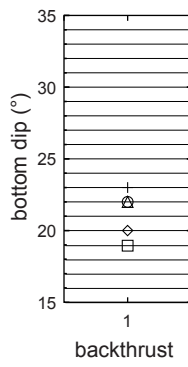
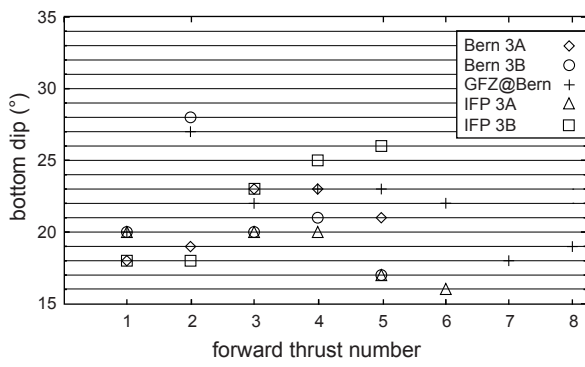
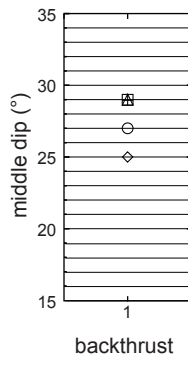
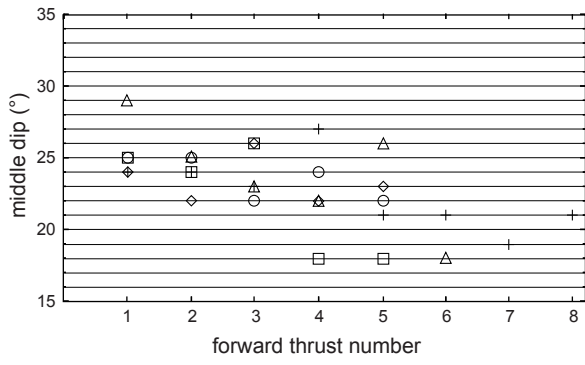
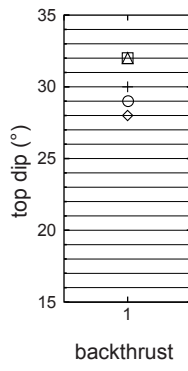
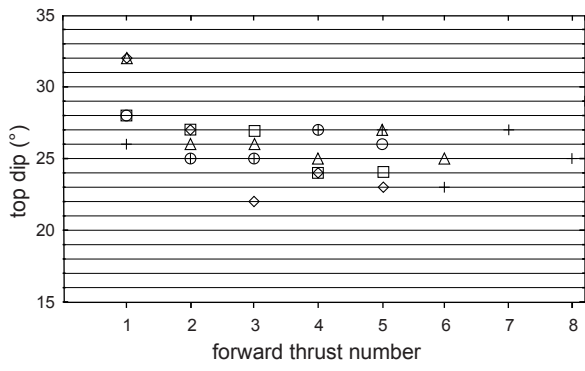


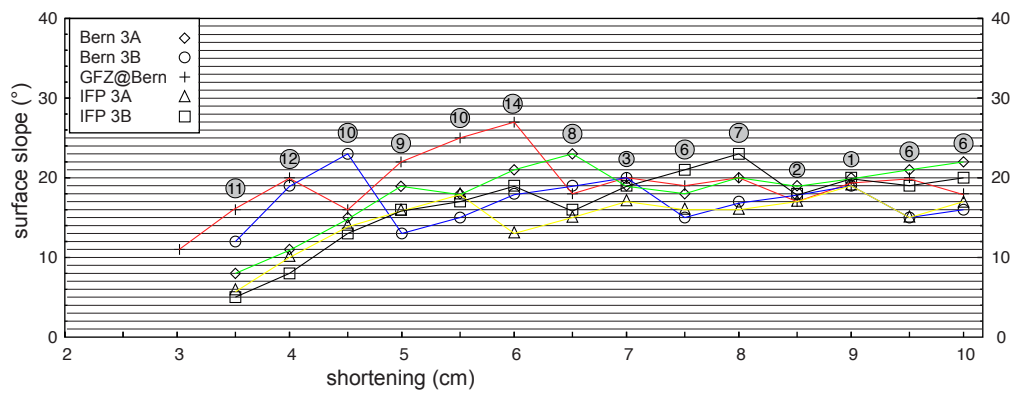


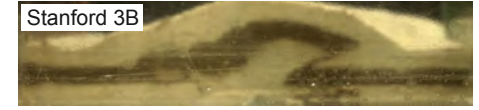
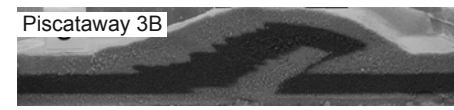
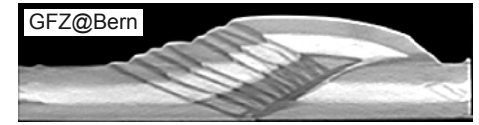
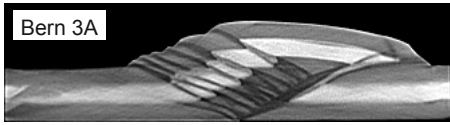


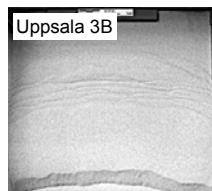
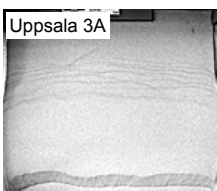
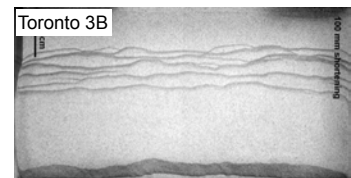
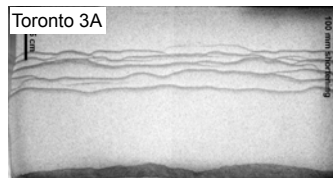
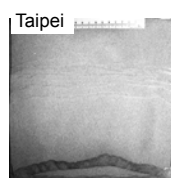
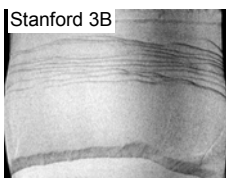
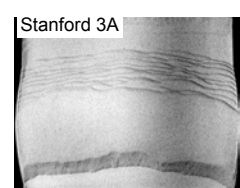
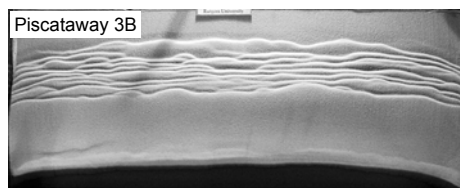
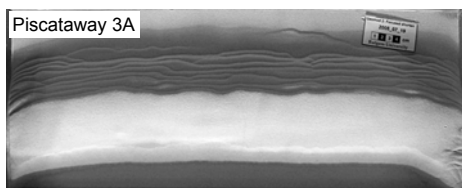
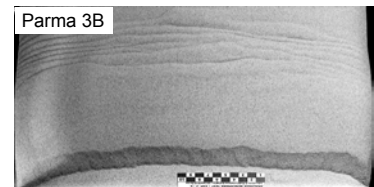
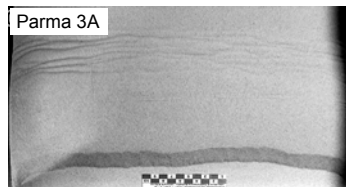
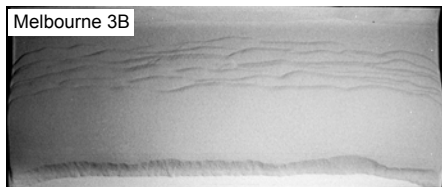
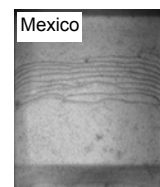
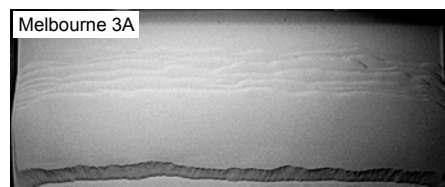
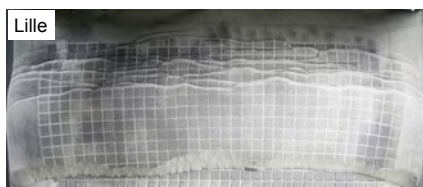
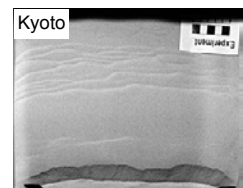
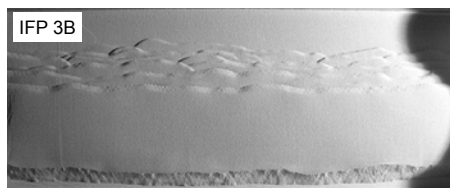
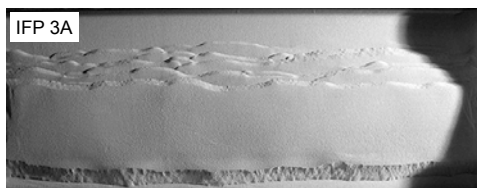
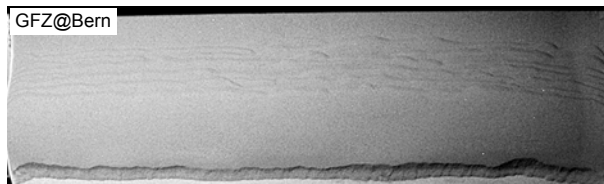
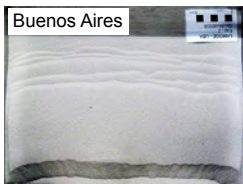
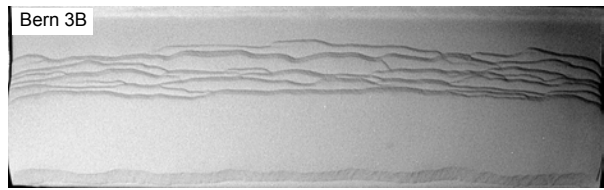
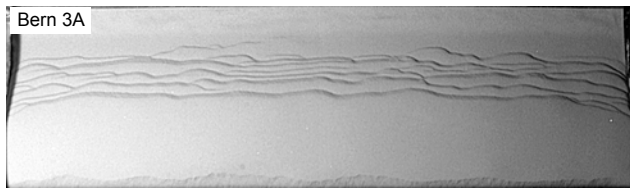


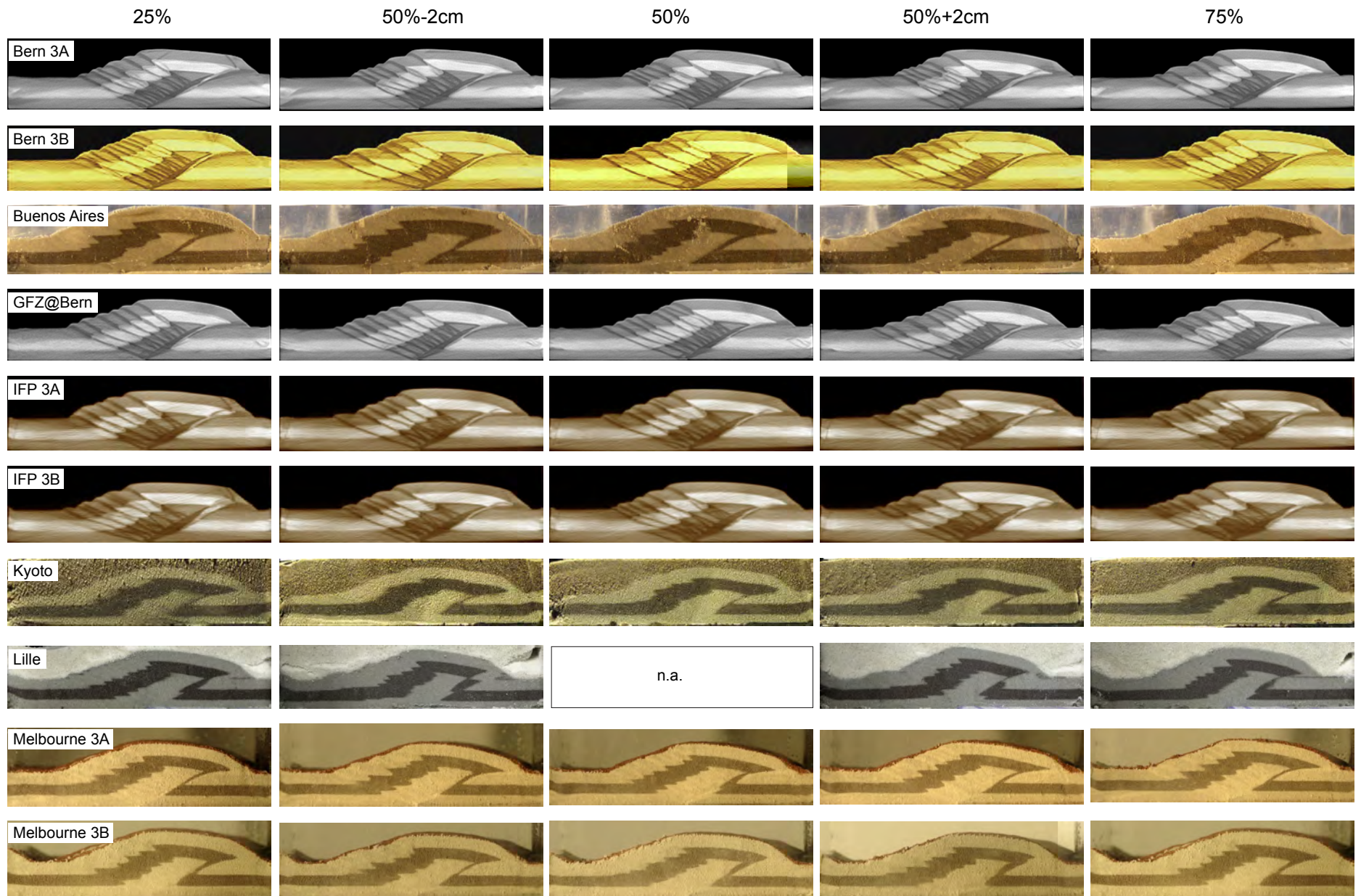












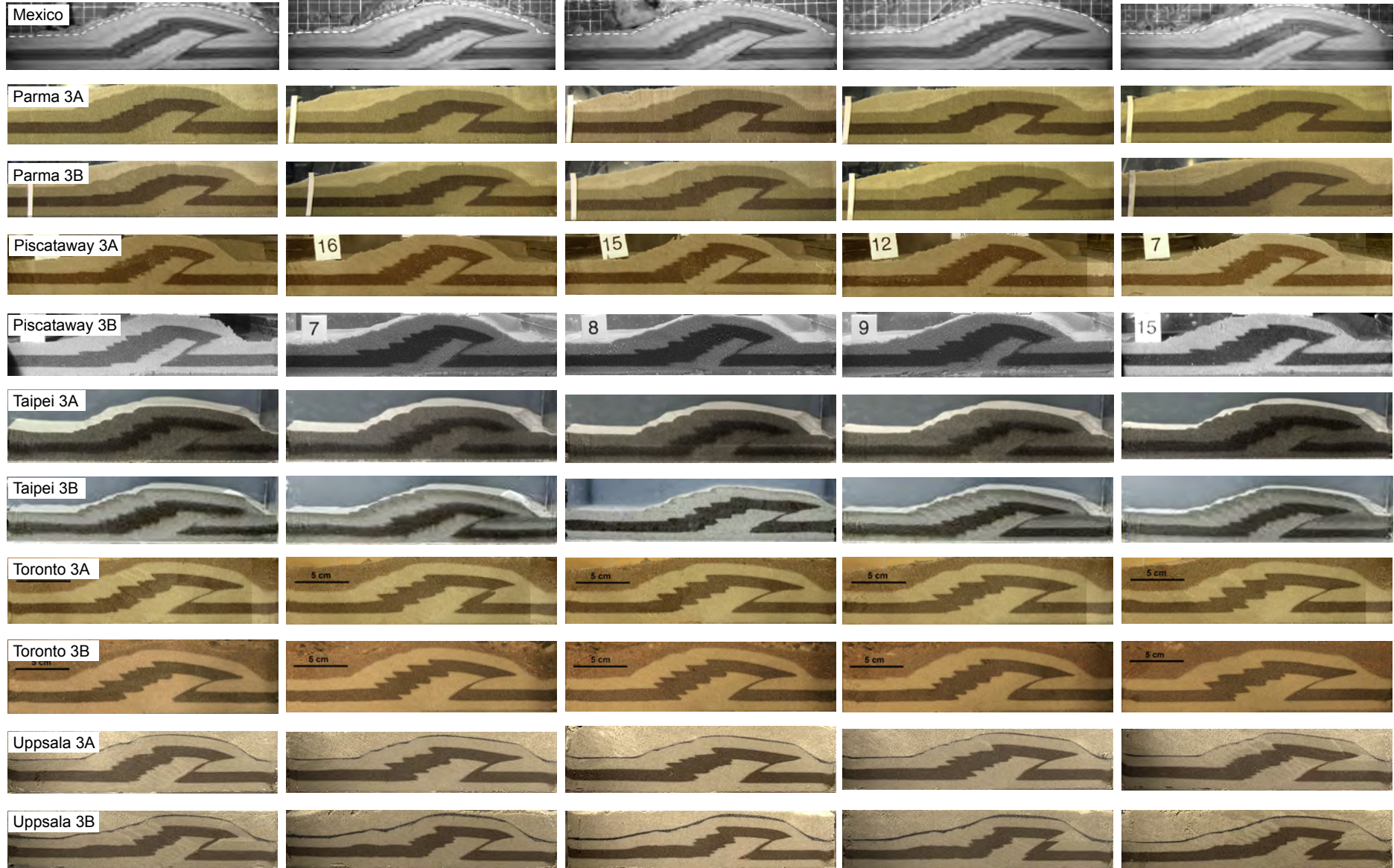
25%

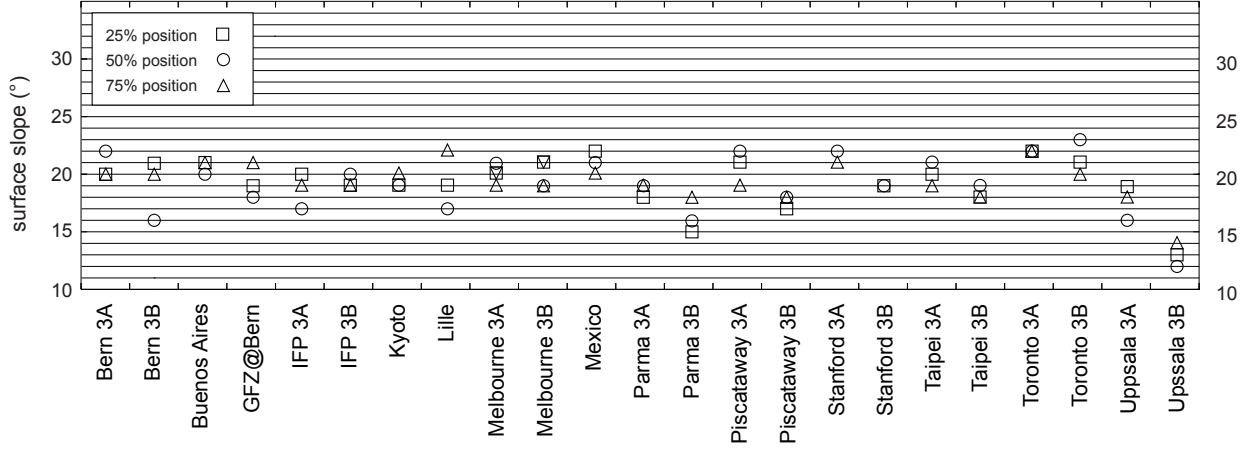
50%-2cm

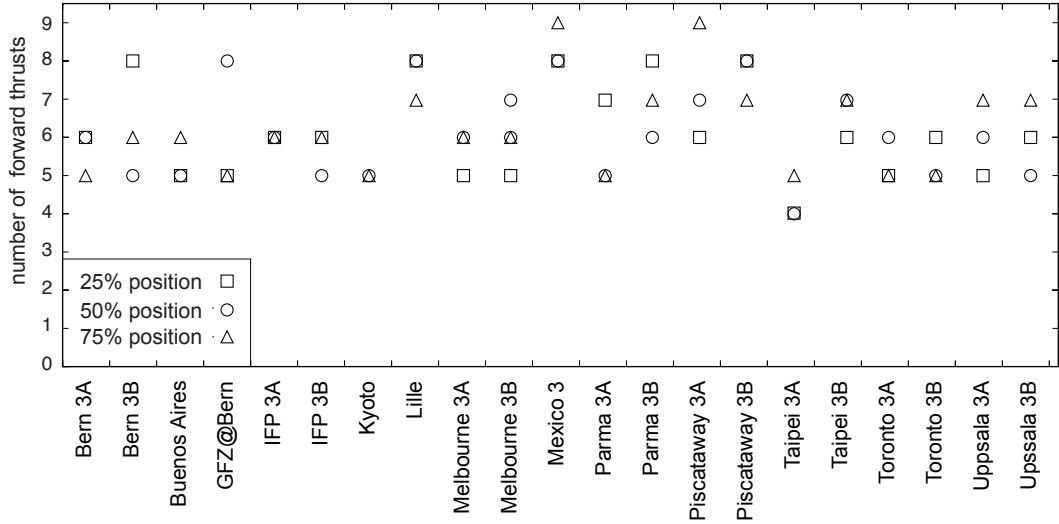
50%

50%+2cm

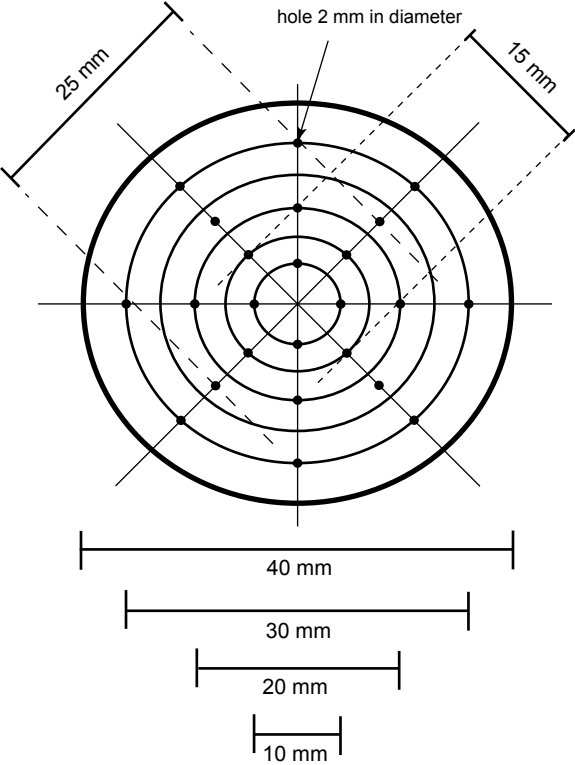
75%



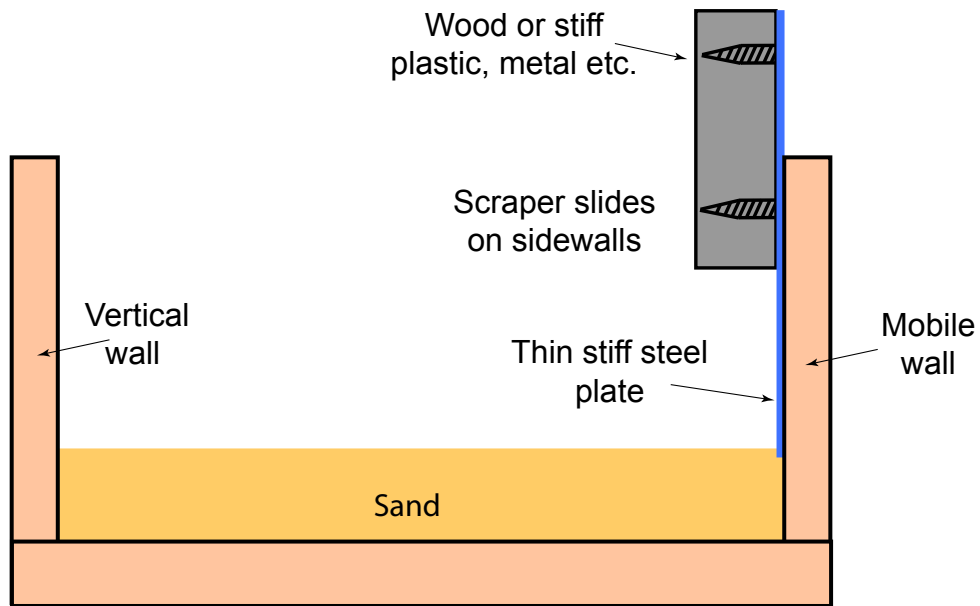




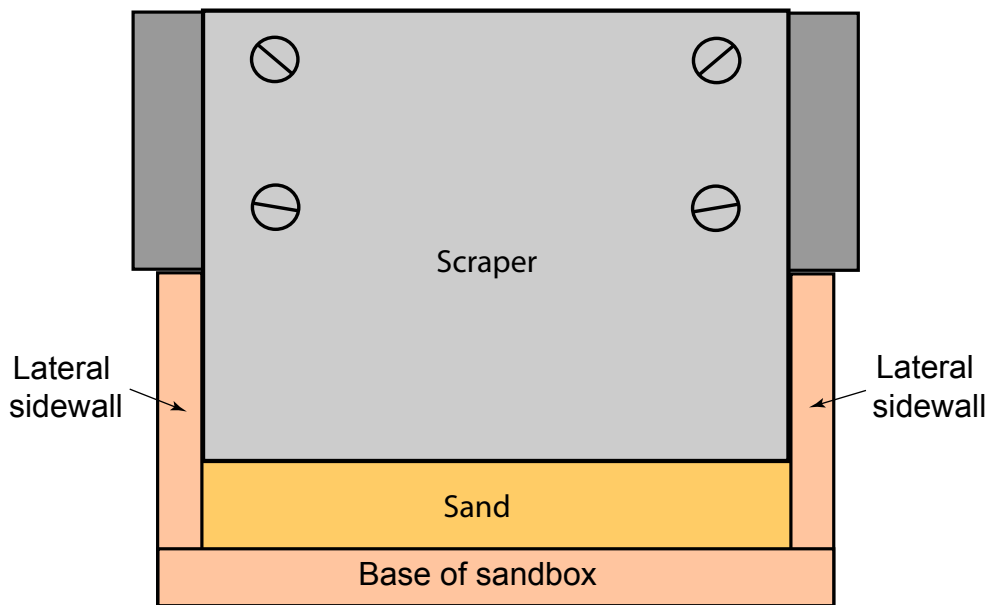
Appendix A-1: Mesh sieve



Appendix A-2: Scraper to remove excess sand



Side view (lateral sidewall omitted for clarity)



Frontal view (vertical mobile wall omitted for clarity)

Mechanical parameter	Quartz sand n = 3	Corundum sand n = 3
Angle of internal friction at peak strength (ϕ_p)	34° - 37°	35° - 36°
Cohesion at peak strength (C_p) in Pa	19 – 69	15 – 28
Angle of internal friction at stable strength (ϕ_s)	30° - 31°	31°
Angle of boundary friction (ϕ_b)	15° - 21°	23° - 25°
Boundary cohesion (C_b) in Pa	14 – 141	23 – 44
Angle of boundary friction at stable strength (ϕ_{bs})	9° - 14°	22° - 24°

Table 1. Range of mechanical properties of quartz and corundum sand obtained with a ring-shear tester. Values are rounded to nearest degree for friction angles and to nearest whole number for cohesion. n is number of ring-shear tests at normal stresses ranging from c. 500 to 2240 Pa.

Laboratory	Room temperature*			Relative humidity			Model width		
	Exp.	(°C)		(%)		(cm)			
	1	2	3	1	2	3	1	2	3
Bern	23	23-24	23-24	60	59-60	54-60	80	80	80
Buenos Aires ¹	23	25	x	53	29	x	32	32	x
Cergy-Pontoise	17-20	17-20	x	60-80	60-80	x	20	20	x
GFZ@Bern ²	24	23	23	54-55	63	57-59	80	80	80
IFP ³	21	21	21	n.d.	n.d.	n.d.	13 [#]	74	74
Kyoto	21	21-22	21	60	55-60	50	30	30	30
Lille	n.d.	n.d.	x	n.d.	n.d.	x	60	60	x
Melbourne	24	24	24	33	32	30-31	60	60	60
Mexico	21	24-26	22	58	57-58	66	20	20	20
Ouro Preto ⁴	20	x	x	56	x	x	30	x	x
Parma ⁵	23	22	22	41	40	40	40	40	40
Piscataway	23	20-25	20-24	n.d.	n.d.	n.d.	61	61	61
Stanford	21-22	21-22	21-22	40-50	40-50	40-50	30.5	30.5	30.5
Taipei	x	19	19	x	58-67	58-60	x	20	20
Toronto	24	24	25	44	45-49	51-53	45	45	45
Uppsala	21	21	21	n.d.	n.d.	n.d.	30	30	30

* rounded to nearest degree, ^x experiment not done, [#] width less than prescribed minimum width of 20 cm, ¹ velocity of mobile wall was 4 cm/h, ² researcher (MR) of Helmholtz Centre Potsdam (GFZ German Research

Centre for Geosciences) performed experiments 1, 2 and 3 using experimental apparatus from Bern, ³ transverse walls in experiment 3 consisted of rubber sheets, ⁴ velocity of mobile wall 2.3 cm/h, ⁵ velocity of mobile wall 5 cm/h, n.d. = not determined

Table 2. Overview of laboratory climatic conditions and model widths. Most laboratories performed experiments 2 and 3 twice, and range of values for room temperature and relative humidity are indicated. Exceptions to the prescribed modeling procedure are also given.