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APPENDIX A: ANALYTICAL METHODS FOR $^{40}\text{Ar}/^{39}\text{Ar}$ AGE DETERMINATION

Mineral separates of white mica, biotite and hornblende were obtained after crushing and handpicking of single grains under a binocular microscope. The minerals were repeatedly cleaned ultrasonically in distilled water and subsequently wrapped in aluminum foils.

The crystals analyzed at Geoazur laboratory (University of Nice Sophia Antipolis) from samples M680A, M717A and M635B were co-irradiated for 30 h in the nuclear reactor at McMaster University in Hamilton (Canada) in position 5c, along with Hb3gr hornblende monitor (1073.6 ± 5.4 Ma, Jourdan et al., 2006). The total neutron flux density during irradiation was 8.8E18 neutron cm$^{-2}$ with a maximum flux gradient estimated at 0.2 % in the volume where the samples were included. Back in Nice, single grains of amphibole and biotite were heated with a CO$_2$ Synrad laser, and the extracted gas was purified in a stainless and glass extraction line using two Al–Zr getters (working at 400 °C and ambient temperature respectively) and a liquid nitrogen cold trap. Isotopic measurements were performed with a VG3600 mass spectrometer and a Daly-photomultiplier system. Blank measurements were obtained before and after every three sample run. The correction factors for interfering isotopes correspond to $(^{39}\text{Ar}/^{37}\text{Ar})\text{Ca} = (7.30 \pm 0.28) \times 10^4$; $(^{36}\text{Ar}/^{37}\text{Ar})\text{Ca} = (2.82 \pm 0.03) \times 10^4$ and $(^{40}\text{Ar}/^{39}\text{Ar})\text{K} = (2.97 \pm 0.06) \times 10^2$. Mass discrimination values range from 1.00474 to 1.00738 ± 1 % (1σ) per dalton (atomic mass unit).

The three samples M776B (biotites), M776B-1 and M776B-2 (white micas) analyzed at SPECTRUM (University of Johannesburg), were vacuum sealed in a ca. 15 cm-long silica glass tube with a 1 cm outer diameter along with other samples and monitors and then irradiated at the NTP radioisotopes SAFARI1 nuclear reactor at Pelindaba, South
Africa, for 20 hours in position B2W with the reactor running at 20 MW. Two 0.2 mg aliquots of each sample were analyzed by stepwise heating, using a defocused beam from a continuous Nd-YAG 1064 nm laser and a MAP 215-50 noble gas mass spectrometer. Signals were measured on a Johnston focused-flow electron multiplier providing excellent linearity in analogue mode. The Fish Canyon sanidine (28.31 ± 0.04 Ma) and Hb3gr amphibole (1080.40 ± 1.10 Ma) (Renne et al., 2010), as well as McClure Mountain amphibole (523.00 ± 1.00 Ma) (Schoene and Bowring, 2006) standards, were used as monitors, yielding within uncertainty limits, identical J-values. A slight flux gradient was monitored and taken into account by placing standards at the bottom and top of the irradiation package. The value for the 40K decay constant derived by Renne et al. (2010) was utilized. Measurement control and data reduction was carried out using an in-house software suite that includes full error propagation by Monte Carlo procedures. Uncertainties are shown at the 95 % (2σ) confidence level.

The criteria for defining plateau ages were as follows: (i) a plateau age should contain at least 70 % of the total released 39Ar, (ii) there should be at least three successive steps in the plateau, and (iii) the integrated age of the plateau should agree with each apparent age of the plateau within a 2σ error confidence interval.

<table>
<thead>
<tr>
<th>Step number</th>
<th>Temp [°C]</th>
<th>% of the total released 39Ar</th>
<th>(Ma)</th>
<th>2σ Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>K468-1</td>
<td>23.90 ± 60.73</td>
<td>248.94 ± 776.72</td>
<td>6.30 ± 3.03</td>
<td>yes</td>
</tr>
<tr>
<td>K468-2</td>
<td>10.55 ± 0.13</td>
<td>0.45 ± 0.44</td>
<td>0.00 ± 0.00</td>
<td>yes</td>
</tr>
<tr>
<td>K468-3</td>
<td>10.89 ± 0.11</td>
<td>0.47 ± 0.04</td>
<td>0.00 ± 0.00</td>
<td>yes</td>
</tr>
<tr>
<td>K468-4</td>
<td>10.58 ± 0.11</td>
<td>0.16 ± 0.09</td>
<td>0.00 ± 0.00</td>
<td>yes</td>
</tr>
<tr>
<td>K468-5</td>
<td>10.22 ± 0.13</td>
<td>0.21 ± 0.24</td>
<td>0.00 ± 0.00</td>
<td>yes</td>
</tr>
<tr>
<td>K468-6</td>
<td>10.43 ± 0.11</td>
<td>0.39 ± 0.10</td>
<td>0.00 ± 0.00</td>
<td>yes</td>
</tr>
<tr>
<td>K468-7</td>
<td>10.53 ± 0.11</td>
<td>0.07 ± 0.05</td>
<td>0.00 ± 0.00</td>
<td>yes</td>
</tr>
<tr>
<td>K468-8</td>
<td>10.72 ± 0.11</td>
<td>0.15 ± 0.18</td>
<td>0.00 ± 0.00</td>
<td>yes</td>
</tr>
<tr>
<td>K468-9</td>
<td>10.90 ± 0.15</td>
<td>0.32 ± 0.71</td>
<td>0.01 ± 0.00</td>
<td>yes</td>
</tr>
<tr>
<td>K468-10</td>
<td>Fusion</td>
<td>11.82 ± 0.15</td>
<td>0.70 ± 0.28</td>
<td>0.00 ± 0.00</td>
</tr>
</tbody>
</table>

TABLE 1A: SUMMARY OF 40Ar/39Ar GEochronology DATA FROM GEoadZ Laboratory (UNIVERSITY OF NICE - SOPHa-Antipolis)
Amphibole M635B (experiment k473) [46.26824°N, 98.1437°E]
J = 0.019259 ± 0.0009876

| Step number | Laser temperature (°C) | 39Ar/40Ar | ± 1σ | 39Ar/40Ar | ± 1σ | 39Ar/40Ar | ± 1σ | CsK | ± 1σ | CKK | ± 1σ | 39Ar/40Ar | (%) | 39Ar/40Ar | (%) | 1σ | Age (Ma) | ± 2σ | Included |
|-------------|------------------------|-----------|------|-----------|------|-----------|------|------|------|------|-----------|------|-----------|------|------|-----------|------|----------|
| 4617_1.1.95A | -                      | -         | 0.2082 ± 0.0726 | 0.14 ± 0.07 | 39Ar/40Ar | ± 1σ | 39Ar/40Ar | ± 1σ | CsK | ± 1σ | CKK | ± 1σ | 39Ar/40Ar | (%) | 39Ar/40Ar | (%) | 1σ | Age (Ma) | ± 2σ | Included |
| 6616_1.1.65A | -                      | -         | 0.0068 ± 0.0008 | 0.14 ± 0.07 | 39Ar/40Ar | ± 1σ | 39Ar/40Ar | ± 1σ | CsK | ± 1σ | CKK | ± 1σ | 39Ar/40Ar | (%) | 39Ar/40Ar | (%) | 1σ | Age (Ma) | ± 2σ | Included |
| 6726_1.1.65A | -                      | -         | 0.0064 ± 0.0008 | 0.14 ± 0.07 | 39Ar/40Ar | ± 1σ | 39Ar/40Ar | ± 1σ | CsK | ± 1σ | CKK | ± 1σ | 39Ar/40Ar | (%) | 39Ar/40Ar | (%) | 1σ | Age (Ma) | ± 2σ | Included |
### APPENDIX B: ANALOGUE MODELLING OF CRUSTAL-SCALE DETACHMENT FOLDS

**Experimental setup**

The analogue modelling apparatus consists of two heating plates confined between two glass panes (1.5 cm thick), a top heat source (several lightbulbs in a row mounted in a steel sheet case), a track of several rotating cylinders over which one of the plates moves laterally between the glass panes and a control unit that allows adjustment of the heating temperature of both plates and the light/heat intensity of the top heat source (Fig. DR1).
Figure DR1. Scheme of the analogue modelling apparatus used for modelling of the crustal-scale detachment folds. Long (movable) plate is one m-long. Both, the moving plate and the backstop can be heated homogenously along their entire length at a temperature adjusted at the control unit. Heating from the top prevented heat loss from the model and maintained a stable temperature gradient across the model.

During the experiment, the long plate (pro-wedge part of the orogen) is moved against the backstop of the stable plate (retro-wedge) by a force of a weight attached to the steel rope pulling the long plate (Fig. DR1). A vertical wall (10 cm high) terminates the long plate and is aimed at supporting the superposed layers that are being deformed by shortening of the multilayer against the backstop. The backstop consists of two segments – a ramp and a plateau. The angle of the ramp and the plateau is adjustable. For the experiment described below, a 4 cm high ramp was inclined at 65° towards the long plate and the plateau was horizontal. Insulating plates (polystyrene) cover the glass panes in order to prevent heat loss before the experimental run.

Analogue materials and experimental preparation
For upper brittle crust, we have used fine-grained, pure quartz sand (grain size 0.017 mm), typically used in crustal-scale physical models (e.g. Sokoutis et al., 2005). The sand is characterized by a density of 1460 kg.m\(^{-3}\), a static friction angle of 32.47\(^\circ\) and cohesion of 95.36 Pa. Partially molten middle to lower crust was simulated by a commercial macrocrystalline paraffin wax with a density of 810 kg.m\(^{-3}\) and a melting temperature of 52°C (Paramo 50-52, manufactured in Czech Republic).

The viscosity of the wax was measured using the VT550 Haake viscometer with coaxial cylinders (MV 1 cylinder) in a temperature range of 44°C to 52°C. The wax is characterized by Newtonian rheology from 46°C to 52°C and dynamic viscosity ranging from 2.03 mPa.s at 46°C to 0.46 mPa.s at 52°C (Table DR2). At lower temperatures (<44°C), the wax solidified, and viscosity measurements were beyond the technical limits of the instrument used. Therefore, for temperatures of the paraffin around 34-44°C, we consider effective viscosities measured by Rossetti et al. (1999) using the uniaxial compression tests on a similar paraffin wax at the same homologous temperatures (T/T\(_m\), where T\(_m\) is the melting point; see Table DR2). Commercial paraffin measured by Rossetti et al. (1999) displayed only a 2°C higher melting point than our wax, and non-Newtonian rheology of solid paraffin at lower temperatures (T/T\(_m\) < 0.7) that ranged between 10\(^5\) to 10\(^8\) Pa.s (Table DR2).

### TABLE DR2. DYNAMIC VISCOSITIES OF THE WAX MEASURED AT TEMPERATURES THAT CHARACTERIZE THE VISCOSITY GRADIENT OF THE PARAFFIN WAX IN THE EXPERIMENT

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>34</th>
<th>38</th>
<th>44</th>
<th>46</th>
<th>48</th>
<th>50</th>
<th>52</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity (mPa.s)</td>
<td>10(^5) Pa.s</td>
<td>10(^5) Pa.s</td>
<td>6.84</td>
<td>2.03</td>
<td>0.85</td>
<td>0.53</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Note: Values for viscosities of 10\(^5\)-8 Pa.s are adopted from Rossetti et al. (1999) and are linked to the same homologous temperatures of the paraffin wax used in this study. Note that the first two values are indicated in Pa.s.

Before the experimental run, a stack of 6 colored wax layers (each 0.5 cm-thick) was placed on the movable heating plate. Sidewalls of the wax multilayer were sprayed with a silicon oil to provide a free-slip surface along the vertical glass panes. In the next stage, the wax multilayer was pre-heated from bottom to top to make sure it is soft and gained enough heat. A horizontal layer of warm sand was then superposed on the moving plate (3 cm-thick) and the stable plate (2 cm-thick) in order to avoid cooling down of the wax. One marker of dark sand was included in the sand layer. The multilayer was then heated to adjust a constant temperature gradient in the column; 52 °C at the base and 45 °C
at the top of the sand layer. The stable plate was pre-heated at a moderate temperature of 45 °C to prevent cooling of the wax at the backstop interface.

In our approach, we attempted to mimic the temperature-dependent viscosity variation with depth in the ductile layer using the heated paraffin wax. Accordingly, the rheological profile from the bottom of the wax layer to the interface with the overlying sand can be divided into three sub-layers: i) completely molten wax with Newtonian rheology and low viscosity of 0.46 mPa.s (Table DR2), ii) mushy, partly crystallized, but still molten wax (6.84 mPa.s at 44°C), and iii) non-Newtonian viscosity of plastic wax in temperature range of 34–44°C defining the stiffest layer in the wax multilayer. Since for this latter stiffest layer, the viscosity could not have been measured using the coaxial cylinder viscometer, we consider viscosity values of a similar paraffin wax measured by Rossetti et al. (1999) at the same homologous temperatures that ranged between 10^5 to 10^8 Pa.s (Table DR2).

For the purpose of the scaling analysis of the experiment with respect to nature, we considered the viscosities of the partly crystallized mushy wax at 44°C with viscosity of 6.84 mPa.s measured by the coaxial cylinder viscometer (Table DR2). This mushy wax in our experiment reflects the migmatitic interlayer between the brittle superstructure of the Chandman dome and the molten to partially molten lower crustal infrastructure. For evaluation of the impact of the gravitational forces on the folding dynamics (using equation 18 of Duretz et al. 2011, see Appendix C), we consider the viscosity of the stiffest layer in the entire multilayer of 10^5 Pa.s (solid, but pseudoplastic paraffin wax at T/T_m ~ 0.7-0.8; Rossetti et al., 1999).

**Scaling relationships**

The model was scaled according to the principles of geometric and dynamic-rheological similarity (Hubbert, 1937; Weijermars and Schmeling, 1986; Sokoutis et al., 2005). The geometric similarity is constrained by the scaling ratio \( l^* = 2 \times 10^6 \) with respect to the 30 km original crustal thickness of the Chandman dome. The accuracy of the dynamic scaling was tested by calculating the non-dimensional numbers given by ratios between the forces acting on the models (Ramberg, 1981). We calculated the ratio between the gravitational and viscous stresses (Ramberg number, \( R_m \); Weijermars and Schmeling, 1986; Sokoutis et al., 2005):
where \( \rho_d \) and \( h_d \) are the density and thickness of the ductile layer (paraffin wax), respectively, \( g \) is the gravity acceleration (\( g = 9.81 \text{ m.s}^{-2} \)), \( \eta \) is the viscosity of the ductile layer and \( \dot{\varepsilon} \) is the strain rate given by the ratio between the mean velocity of convergence \( V \) and the thickness of the ductile layer \( h_d \). Scaling of the brittle deformation was achieved by calculating the ratio between the gravitational stress and cohesive strength (\( R_s \); Ramberg, 1981; Sokoutis et al., 2005):

\[
R_s = \frac{\text{gravitational stress}}{\text{cohesive strength}} = \frac{\rho_b g h_b}{\tau_c}
\]

where \( \rho_b \) and \( h_b \) are the density and thickness of the brittle layer, respectively, \( g \) is the gravity acceleration and \( \tau_c \) the cohesive strength of the brittle layer. For a correctly, dynamically scaled model, the \( R_m \) and \( R_s \) calculated for both, the model and the original (Chandman dome), respectively, should be similar (Table DR3), within the same order of magnitude.

<table>
<thead>
<tr>
<th>TABLE DR3. SCALING PARAMETERS FOR BRITTLE AND DUCTILE DEFORMATION OF THE EXPERIMENT. SYMBOLS ARE DEFINED IN THE TEXT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper crust (sand in the experiment)</td>
</tr>
<tr>
<td>( \rho_\text{b} ) (kg.m(^{-3}))</td>
</tr>
<tr>
<td>Model</td>
</tr>
<tr>
<td>Nature</td>
</tr>
</tbody>
</table>

Note: The viscosity of the ductile layer in the experiment corresponds to the wax paraffin viscosity measured at 44°C (Table DR2)

The scaling analysis (Table DR3) compares the viscosities (\( \eta \)) of the partially crystallized wax measured at 44°C (6.84 mPa.s, Table DR2) and a migmatite, for which the viscosity
is indirectly estimated from the viscosity of a suspension of a hydrous granite (hydrous rhyolitic melt containing ~2 wt.%, Giordano et al., 2008) of ~10^7 Pa.s and 60-80 vol.% of crystals that increases the effective viscosity of the crystal-free melt 6-7 orders of magnitude to maximum ~10^{14} Pa.s (Costa et al., 2009). This scaling analysis (Table DR3) shows comparable values of both the R_m and R_s of the experiment and natural original, respectively. Alternatively, for the dynamic scaling analysis of the ductile layer, we can consider the viscosity of the completely molten wax (0.46 mPa.s at 52°C) as an equivalent to the granite melt of ~10^8 Pa.s (containing 1.5 wt.% water, corresponding to the 5.15 mol.% water of migmatite sample M109P72 of Broussolle et al., 2015) with 40-50 vol.% crystals that will render effective viscosity of the melt+crystal suspension of ~10^{13} Pa.s (Giordano et al., 2004, 2008; Costa et al., 2009). Calculating the R_m with the latter values for the experiment and original (nature, Chandman dome), will give again values within the same order of magnitude.

In summary, we can suggest that the rheological stratification of the sand and the wax fairly well mimics the rheological stratification before the folding of the Chandman dome. The partially molten wax implements a viscosity gradient from the completely molten layer at the bottom of the lower crust to a partially molten layer close to the interface between the weak lower crust and brittle upper crust. The scaling analysis also shows that the rheological properties, dimensions and timescales are within reasonable ranges to consider the experiment in terms of close dynamic similarity with the folding of the Chandman dome.

**APPENDIX C: CALCULATION OF DIAPIRC VELOCITY AND BACKGROUND VELOCITY**

In order to constrain potential contribution of the diapiric forces to the formation of the detachment fold in the analogue model, we use equation 18 of Duretz et al. (2011). The vertical velocity linked to formation of a Rayleigh-Taylor instability \(V_{RT}\) is expressed against the density ratio between the layers \(\delta \rho\), the gravity \(g\), the height of the initial perturbation of the interface \(A\), the thickness of the crust \(H_{crust}\), the viscosity of the stiffest layer \(\eta_{MC}\) and the background strain rate \(\dot{\varepsilon}_{BG}\).
The viscosity of the stiffest layer ($\eta_{MC}$) is $10^5$ Pa.s (following measurements of Rossetti et al. 1999, see Appendix B), the initial perturbation of the interface A is chosen at 0.003 m, corresponding to 10% of the total wax thickness, background strain-rate is $\frac{(L_t - L_0)}{L_0}/dt = \frac{(0.6 - 0.96)/0.96}{4500} = -8.333305 \times 10^{-5}$ s$^{-1}$.

The background velocity is defined as total shortening of the box divided by total time of experiment.

According to these calculations, the rate of box shortening is ~30 million time faster than diapiric rate.

**APPENDIX D: ANALYTICAL SOLUTION DESCRIBING GEOMETRICAL EVOLUTION OF THE DETACHMENT FOLD**

Knowing $H$, $h$, $C_h$, $LZW$ and $\theta$, the initial length of limbs ($L_0$) and fold crest width ($C$) can be written as follows (see figure 13 for explanation of the different symbols):

\[
L_0 = \frac{LZW}{\sin(\theta)}
\]

\[
C = C_h + 2 \times \frac{(H-h)}{\tan(\theta)}
\]

Note that the initial width of the detachment fold is given as $W_0 = C + 2 \times L_0$.

With increasing displacement $D$, the area/volume of fold core ($A$) is a function of fold amplitude ($a$), inner fold crest width ($C_h$), length of fold limb ($L_D$) and its angle ($\alpha$):

\[
L_D = \frac{LZW}{\sin(\pi - \theta - \alpha)}
\]

\[
a = L_D \times \sin(\alpha)
\]

\[
i = L_D \times \cos(\alpha)
\]

\[
A = a \times (i + C_h)
\]

The corresponding displacement is $D = 2 \times (L_0 - i)$.
Assuming that there is not volume change within the folded layer, the evolution of area/volume of the fold core $A$ in respect to either the limb angle ($\alpha$) or displacement (shortening %) is not balanced with the displaced layer area/volume $S = D \times h$. The actual difference between $A$ and $S$ reflects the potential to mass transfer into or out of the fold core. See text for details.

REFERENCES CITED


Renne, P. R., Mundil, R., Balco, G., Min, K., and Ludwig, K. R., 2010, Joint determination of 40K decay constants and $^{40}$Ar*/$^{40}$K for the Fish Canyon sanidine standard, and improved accuracy for $^{40}$Ar/$^{39}$Ar geochronology: Geochimica et Cosmochimica Acta, v. 74, no. 18, p. 5349–5367, doi:10.1016/j.gca.2010.06.017.


