

## GSA DATA REPOSITORY 2020065

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Supplementary material to - Braathen and Osmundsen, “**Extensional tectonics rooted in orogenic collapse: Long-lived disintegration of the Semail ophiolite, Oman**”, published in *Geology*, vol. 48, 2019.

### Introduction to Supplementary datasets

This repository relates to the article by Braathen and Osmundsen (2019), “Extensional tectonics rooted in orogenic collapse: Long-lived disintegration of the Semail ophiolite, Oman”, published in *Geology* (<https://doi.org/10.1130/G47077.1>). Enclosed figures present evidence from some key locations within the central to east Northern Oman Mountains. Photographs annotated with line drawings and text, schematic cross-sections, and stereo plots (equal area, lower hemisphere) of structural datasets, add information to the article. Positions are given for points of observation, and the figure captions guide the reader to subjects addressed in the article.

Five figures summarize key observations as a basis for the work. This Repository is not providing the full database; the focus is on briefly establishing a novel tectonic model for the central to east Oman Mountains with significant generic implications for extensional collapse of orogens.

The discussed sites located with coordinates are linked to figures in Braathen and Osmundsen (2019) as follows:

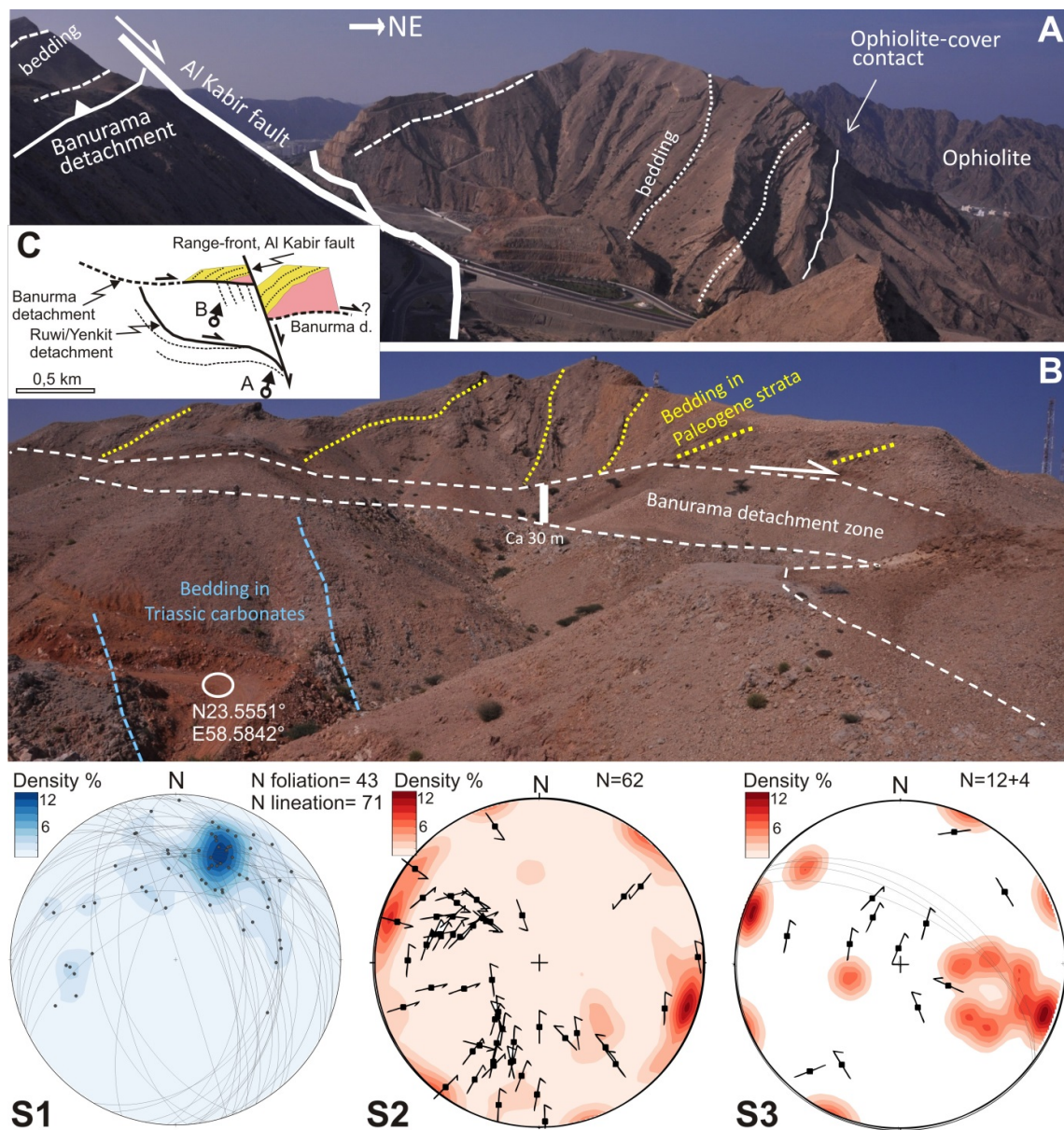
*Supplementary Figure 1:* Banurama detachment and Wadi Al Kabir fault; outlined in the map of Fig. 2 and shown in cross-section C-C’ of Fig. 3.

*Supplementary Figure 2:* Asmaiyah detachment; outlined in the map of Fig. 2 and shown in cross-section D-D” of Fig. 3 and in cross-section X-X’ of Supplementary Fig. 3.

*Supplementary Figure 3:* Wadi Kabbah fault and Asmaiyah detachment; cross-section X-X’ is located in the map of Fig. 2.

*Supplementary Figure 4:* An Naba detachment; outlined in the map of Fig. 2 and shown in cross-section E-E’ of Fig. 3.

*Supplementary Figure 5:* Tectonic evolution proposed for the extensional province, adding a tentative chronology to Fig. 4.



**Supplementary Figure 1: Observations of Banurama detachment and Al Kabir fault.**

The Banurama detachment is best seen in the outskirts of Muscat, on the ridge west of Wadi al Kabir (N23.554417°-E 58.599095°; N23.554203°-E 58.585435°). For a regional perspective, see cross-section C-C' of Fig. 3 (Braathen and Osmundsen, 2019). The Banurama detachment juxtaposes moderately to steeply dipping beds of Paleogene deposits resting on the Semail Ophiolite, with underlying Triassic and Jurassic marbles (low-grade mainly carbonates are termed marbles for clarity). The Banurama detachment is truncated by the Wadi Al Kabir fault (eastern segment of the Range-front fault).

(A) From the NE/right, the photograph shows the Semail Ophiolite, the fundamental unconformity on the top of the ophiolite, and steeply southerly dipping beds in Late Paleocene to Early Eocene sedimentary units (Jafnayn Formation). This succession is offset by the Wadi

Al Kabir fault, which is a nearly planar normal fault with domineering dip-slip top-NNE kinematics, subordinate oblique sinistral-normal top-NNW slip, as deduced from slip-linear plots of slickensides recorded along the well-exposed fault plane (stereoplot S2). In the footwall of the Al Kabir fault, an outlier/klippe of the ophiolite-sedimentary succession is present.

(B) Photograph (see coordinates) showing the Banurama detachment, representing a 15-30 m thick shear zone that separates steeply NNE-dipping Triassic-Jurassic marbles underneath from steep to moderately southerly dipping bedding of Paleogene sedimentary units in the hanging wall of the detachment. This strongly truncating nature of the detachment is consistent for the entire N-S length of the outcrop, exceeding 500 m. The detachment zone is made up of talc and serpentine breccias and foliated cataclasites (ophiolite affinity), mixed with layers and pods of other units that are highly brecciated. Slickensides and rare stretching lineations in talc suggest top-NNE transport on the detachment (stereoplot S3).

(C) Schematic cross-section illustrating the geometric relationships of this area. Note view-points for photographs 'A' and 'B'. The Banurama detachment is truncated by the Al Kabir fault, the latter of which has a throw of ca 500 m as established by offset of the top-ophiolite unconformity with cover sediments (in cross-section), hence deviating from the ca. 150 m reported by Mattern and Scharf (2018). Several semi-brittle to plastic shear zones/detachments can be identified by low-angle truncation of layers in the Mesozoic succession (mainly marbles) and at places by metamorphic discontinuities (see Warren and Millet, 2007, with references) in the Siah Hatat dome, i.e. below the Banurama detachment. Shear zone kinematics as shown by typical shear-sense indicators is top-NNE and parallel to a locally well-developed stretching lineation (e.g., Jolivet et al. 1998) as seen in the stereoplot S1. Of these, the Ruwi-Yiti-Yenkit shear zone system as shown in the sketch-section is sub-parallel to bedding in the folded marbles. As the Banurama detachment in its present orientation is near-horizontal and semi-planar, it cuts these folds and shear zones.

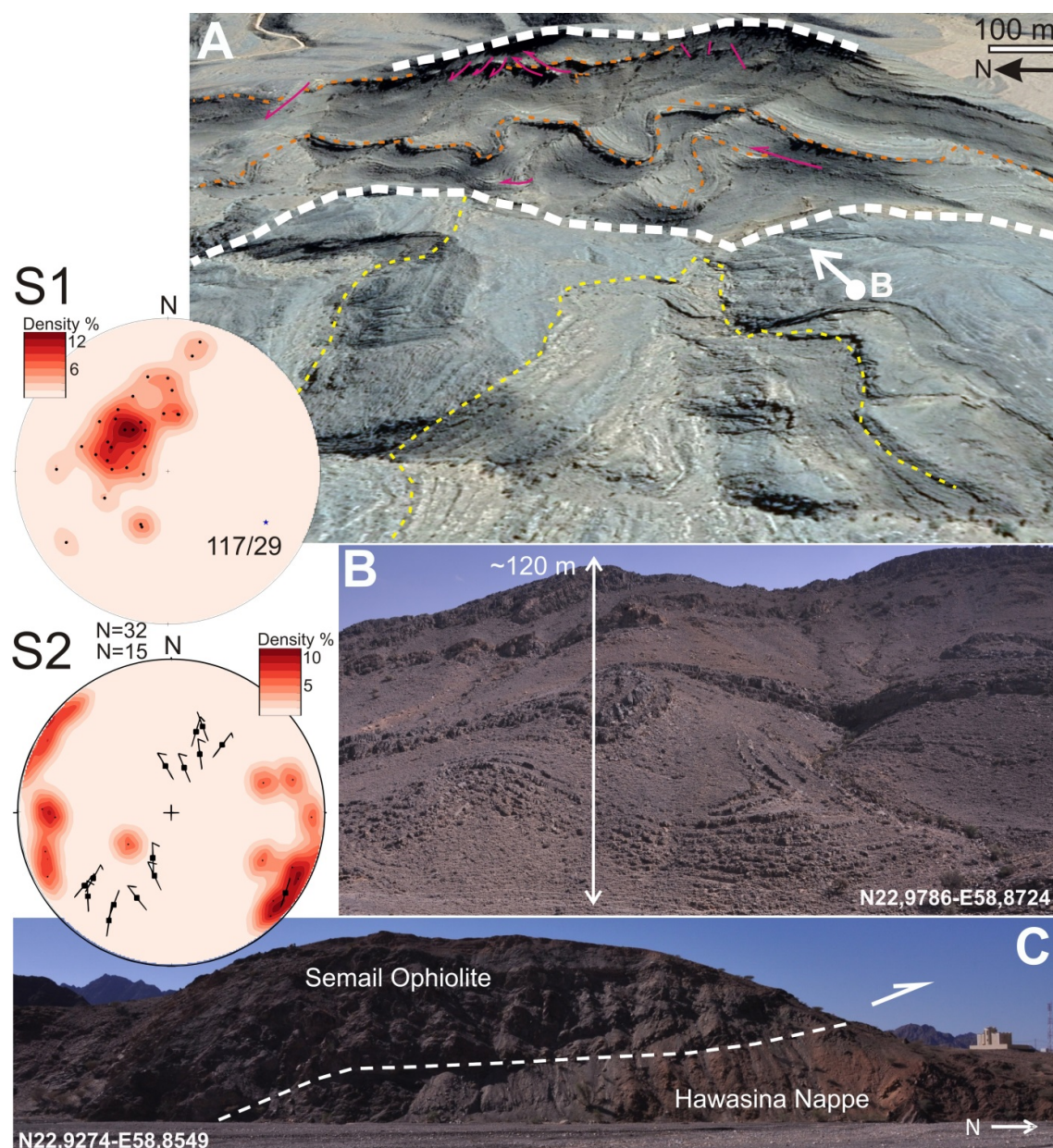
(S1) Stereoplot (lower hemisphere, equal area) of the foliation (planes) and a well-developed stretching lineation (dots and contours) in low-grade metamorphic units below the Banurama detachment, including the Ruwi-Yiti-Yenkit shear zone system. Folding of the succession reveals an overall fold axis (intersection of planes) parallel to the lineation, which has a distinct NNE trend. Observations of fabrics in the NE part of the Saih Hatat dome correspond to observations in accounts of Jolivet et al. (1998), Warren and Miller (2007) and Cornish and Searle (2017).

(S2) Stereoplot of slickensides recorded along the Wadi Al Kabir fault, plotted as slip-linears and contoured poles to M-planes. The slickensides suggest a domineering normal, down-NNE movement on the fault. A subordinate normal-sinistral movement trend can also be distinguished. Overprinting slickensides indicate the latter event postdates the normal-slip event. The plotting method shows the slip-line on the pole to the recorded fault plane. M-planes are designed as a surface hosting both the slip-line and the pole to the fault surface, representing the plane of tectonic transport. Contoured poles to M-planes hence can be used to identify the domineering axis perpendicular to transport (proxy for the intermediate principal stress axis  $\sigma_2$ ). For the plotting method, see Goldstein & Marshak (1988) and Braathen and Bergh (1995).

(S3) Stereoplot of slickensides recorded along the near-horizontal Banurama detachment, shown as slip-linears and contoured poles to M-planes. Bedding in low-grade carbonates/marbles below the detachments is plotted as planes and shows a steep NNE dip. The slip-linears suggest an overall top-NNE direction of transport along the Banurama detachment, which conforms to the stretching lineation in the underlying low-grade rocks of



the Saih Hatat dome hosting the Ruwi-Yenkit-Yiti shear zone system, as well as to the direction of domineering slip on the Wadi Al Kabir fault.



### Supplementary Figure 2: Observations of the Asmaiyah detachment.

The Asmaiyah detachment is best seen in the highlands up to the north of Wadi Kabbah (N22.9786°-E 58.8724°). For a regional perspective, see cross-section D-D'' of Fig. 3 (Braathen and Osmundsen, 2019).

(A) In an earth-view, the more than 100 m thick shear zone is characterized by intense tight folding, and numerous reverse and normal offset discrete faults/shear zones. The entire shear zone with bounding units is folded into a gentle, upright anticline. Underlying Mesozoic marbles are folded into an open to tight S-verging monocline, which is truncated by the shear zone. Bedding in overlying marbles orients sub-parallel to the shear zone and hence conforms to the gentle anticline.

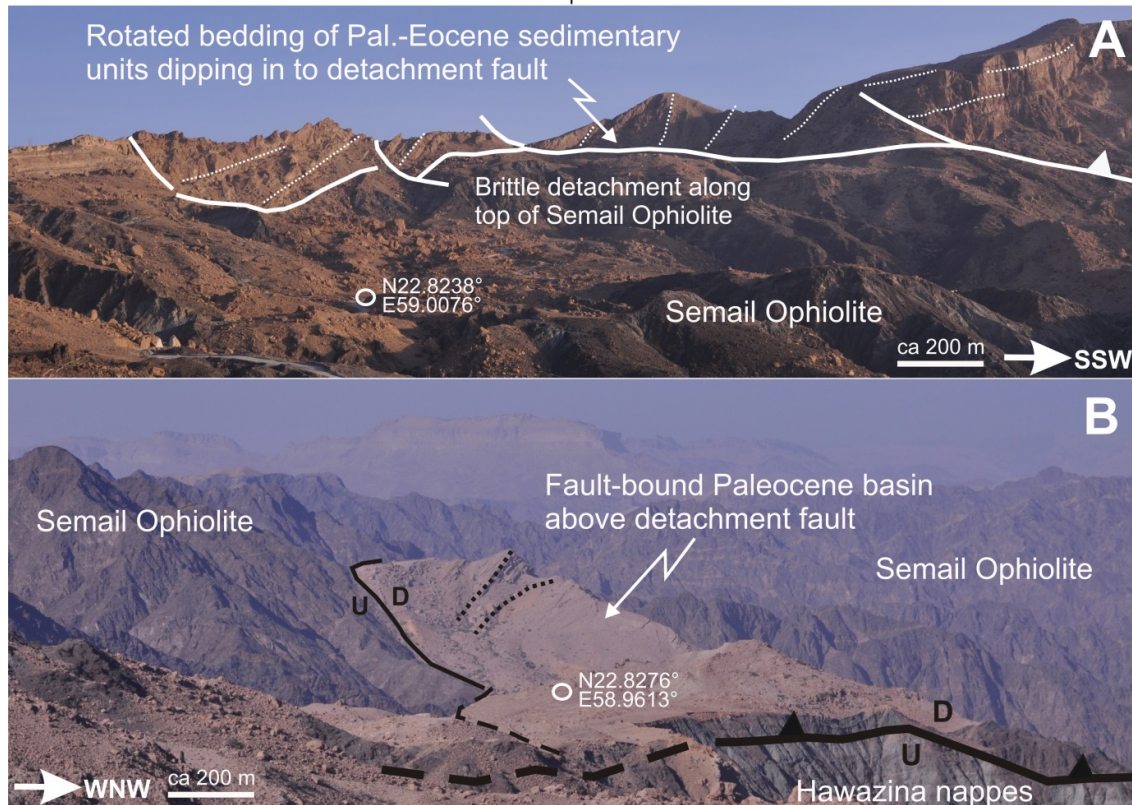
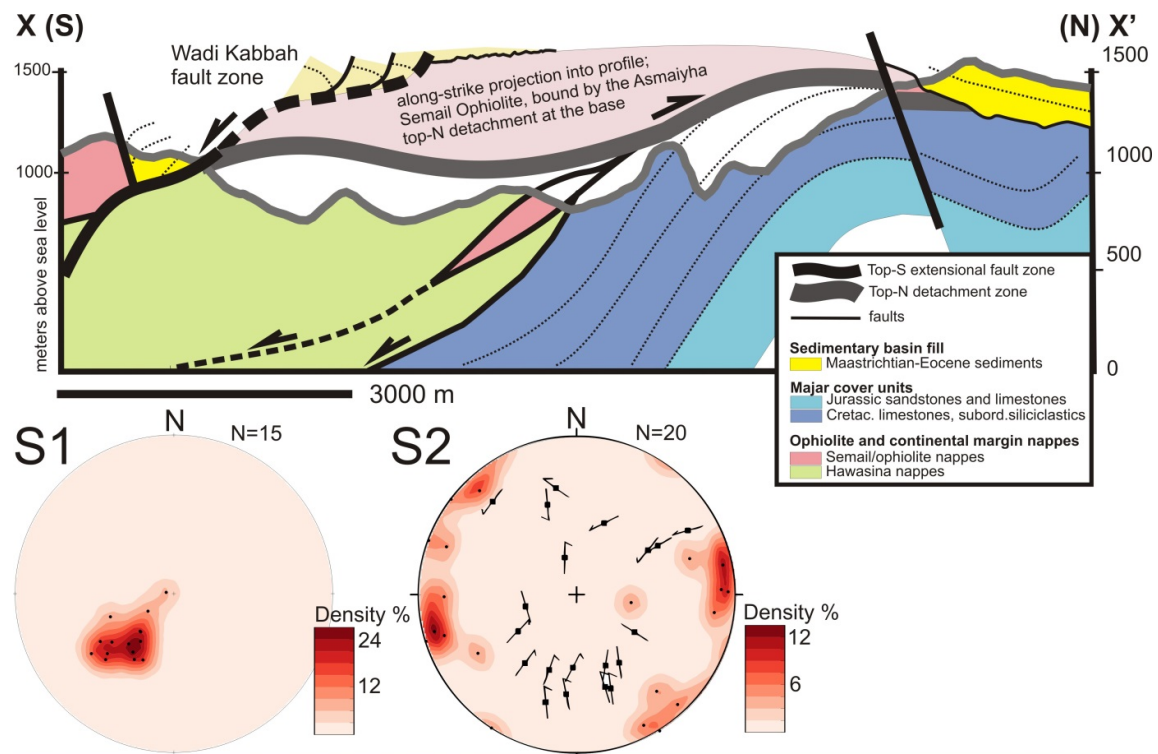
(B) Photograph of folded bedding within the shear zone. Folds have a distinct NNE vergence, as shown by the stereoplot S1 that reveals a gently ESE-plunging fold axis from poles to bedding within the shear zone, which appears to be sub-parallel to the gentle anticline.

(C) Asmaiyah detachment seen west of the Asmaiyah village in the Wadi Kabbah. The Semail Ophiolite is placed on top of the Hawasina nappes by a shear zone that show top-NNE tectonic transport, as suggested by fault kinematics shown in stereoplot S2.

(S1) Stereoplot of poles to bedding (dots) that are contoured in the Asmaiyah detachment from the site in the earth-view 'A'. Distribution of poles to bedding conforms to a moderately ESE-plunging fold axis, which is oriented perpendicular to the NNE-directed tectonic transport suggested by vergence of the folds.

(S2) Stereoplot of slickenside data plotted as slip-linears. Contours are based in poles to M-planes. The dataset shows a distinct top-NNE to NE transport, which conforms to the kinematics suggested from the folds in S1.





**Supplementary Figure 3: Cross-section showing details of the Wadi Kabbah fault and Asmaiyah detachment.**

The X-X' schematic cross-section is N-S oriented and located in the map of Fig. 2 (Braathen and Osmundsen 2019). The cross-section combines information from the steep slope just east of the cross-section line (projected ca. 300 m westward out in the air, shown with diffuse colours, see photograph 'A') with data from the topographic profile. The Asmaiyah detachment cuts successively down-section into tectonostratigraphic deeper units to the north, excising the Hawasina nappes and placing the Semail Ophiolite on top of "autotochthonous" Cretaceous limestones/marbles. The detachment dips moderately south other places in the region, but in this location and the site shown in Supplementary Figure 2, a near horizontal orientation is encountered towards the north. For both these sites the detachment cuts into an underlying south-verging monocline (Halouf monocline). The resultant truncation is consistent with a down-north normal shear zone. Farther north, both the detachment and the deep-seated monocline are truncated by the basal unconformity below Late Palaeocene sedimentary units (Jafnayn Formation). Kinematics of the detachment can be further unravelled by slickensides and rare stretching lineations combined with shear-sense indicators, showing a NNE transport direction (stereoplot S2 in Supplementary Figure 2).

The Wadi Kabbah fault is a regional, segmented fault zone that can be traced basically continuously along the Wadi Kabbah. This is a top-S normal fault, in accordance with accounts of Searle (2007). In the study area of the cross-section, the fault has a flat-ramp-flat geometry as it cuts down through the Semail Ophiolite and the underlying Asmaiyah detachment, and into the Hawasina nappes. Rotated bedding, rollover folds and wedging in sedimentary units of the hanging wall (photographs in 'A' and 'B') suggest growth-faulting spanning the Late Palaeocene to Middle Eocene (Jafnayn and Seeb formations). Folding in the sedimentary units is around a south-easterly axis, as shown in stereoplot S1. Slip-linear plot of slickensides suggest overall southerly transport for this area and for other locations along the Wadi Kabbah fault, as seen in plot S2.

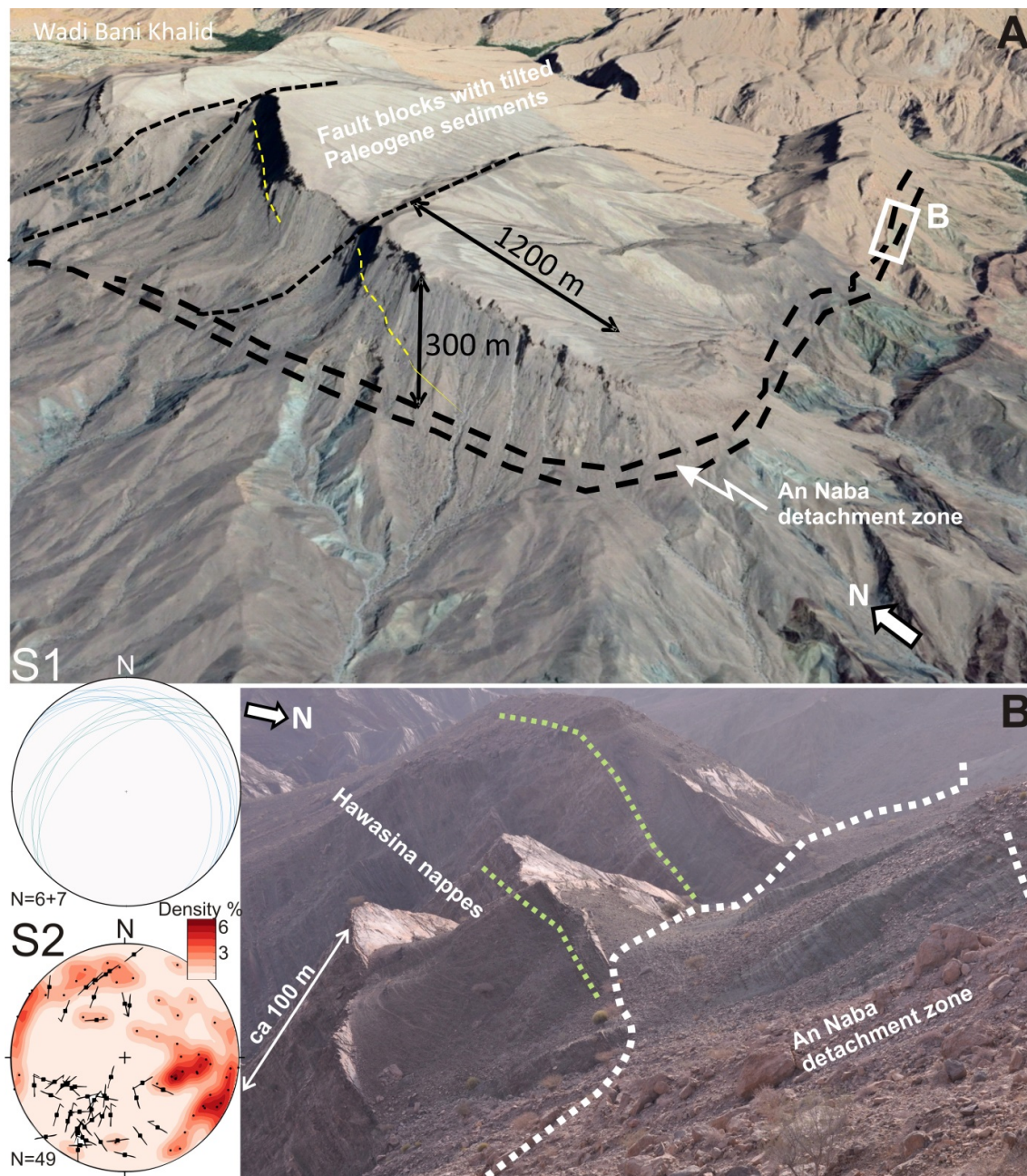
(A) Photograph (located with coordinates) with line drawing showing the Wadi Kabbah detachment fault. Beds of Palaeocene to Eocene units (plotted in S1) dip moderate to steeply into the near-horizontal fault zone. The detachment fault defines the top of the Semail Ophiolite; it comprises 30-40 m thick breccias of partly altered ultramafic rocks.

(B) Photograph with line drawing showing a half-graben basin down-faulted in to the Semail Ophiolite. The fault roots in the top-S Wadi Kabbah detachment fault, the latter of which separates the hanging wall ophiolite from footwall Hawasina nappes.

(S1) Stereoplot of poles to bedding for sedimentary units above the Wadi Kabbah detachment fault, as seen in photograph 'A'. Bedding dips moderately to steeply into the nearly horizontal fault zone. Spread in orientation suggests folding is around an ESE to SE gently plunging fold axis.

(S2) Stereoplot of slickenside data recorded along the Wadi Kabbah detachment fault. South and north-dipping normal-slip slickensides are interpreted as synthetic and antithetic shear fractures in the damage zone of the fault, signifying overall top-S kinematics on the major fault as seen by offset of lithological boundaries and Palaeogene basins in the hanging wall.





#### Supplementary Figure 4: Observations of An Naba detachment.

The An Naba detachment zone is best seen south of Wadi Bani Khalid, where well-exposed ridges are complementary to outcrops around the An Naba village farther west. A regional perspective is given in cross-section E-E' of Fig. 3 (Braathen and Osmundsen, 2019).

(A) Earth-view of the An Naba detachment, showing three fault blocks bound by normal faults. The blocks host Hawasina nappes truncated by an angular unconformity and overlain by Late Paleocene to Middle Eocene sedimentary rocks (Jafnayn Formation). In all three blocks there is a moderate southerly dip of bedding and the unconformity, down towards the underlying moderately north-dipping detachment. The block-bounding faults that offset the

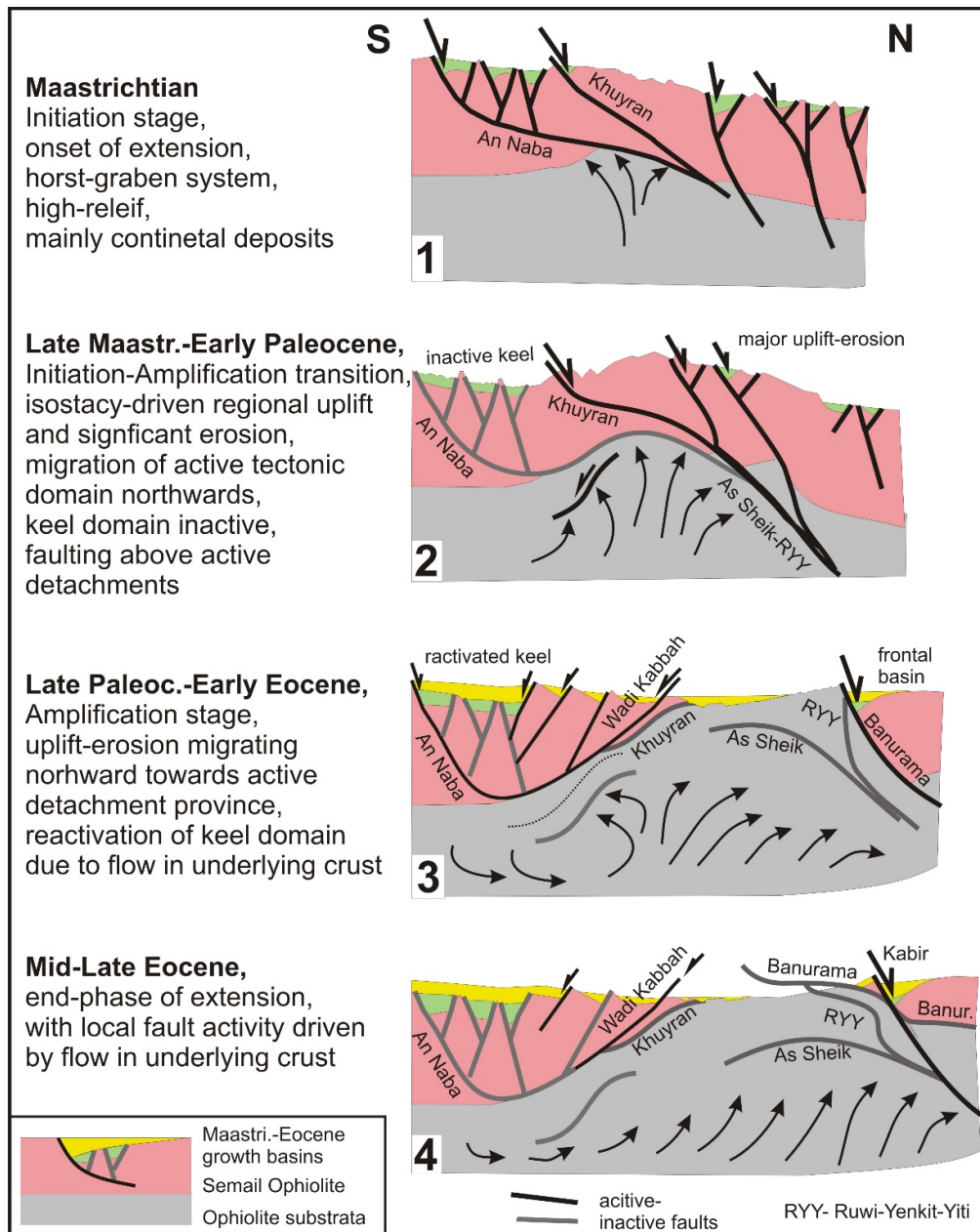


sedimentary rocks in a down-N direction appear to root in the shear zone; they do not offset the detachment.

(B) An Naba detachment zone seen in rock-slopes west of Sayq village (N22.514012°-E59.102813°). This shear zone consists of greenish-yellow slate with stringers of various rocks, with relict bedding paralleling a semi-penetrative fabric. Noticeable, beds in the underlying Hawasina nappes are intensely folded with a northerly vergence; these folds and bedding in the Hawasina nappes are truncated by the semi-planar shear zone.

(S1) Stereoplot of bedding in the Hawasina nappes (green planes) and the fabric in the An Naba detachment (blue planes) near Sayg village, as shown in photograph 'B'. Folded lithological contacts within the Hawasina nappes are truncated by the detachment zone.

(S2) Stereoplot of slickensides data as slip-linears, recorded around the An Naba and Sayq villages. Contoured poles to M-planes for the dataset suggest top-N to top-NE movement on the detachment.



**Supplementary Figure 5: Tectonic evolution proposed for the extensional province.**

The step-wise reconstruction is based on cross-section D-D'' of Fig. 3 (Braathen and Osmundsen 2019). The schematic cross-sections have a significant vertical exaggeration. The tentative evolution proposes a timing and outlines the importance of major shear zones and lower-plate folds/monoclines during progressive northward migration of the domineering active tectonic province. Flow in the lower plate (below detachments) is suggested by arrows. An early Initiation stage (1) progresses into the Amplification stages (2-4) during gradual uplift and exhumation of the Semail Ophiolite's substrata. Notice that the sedimentary successions in many of the basins of Northeast Oman are poorly dated; hence there are challenging links between mineralogical geochronology and biostratigraphy.

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