[PS]Impact of Heterogeneous Storm Event Deposits on Fluid Flow Behaviour of Late Jurassic Arab-D Reservoir, Saudi Arabia*

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Abstract

The Late Jurassic Arab-D reservoir is highly prolific in several supergiant oil and gas fields in the Middle East. An outcrop analogue of equivalent age in Central Saudi Arabia shows depositional facies and stratigraphic architecture similar to those inferred in the subsurface. This analogue is studied using a digital outcrop model, to understand and quantify facies and related rock property distributions, and their impact on flow behaviour in storm dominated, shallow-marine carbonates of the lower to middle Arab-D reservoir. Outcrops reveal a succession of thin (0.5-1 m) fining upward cycles formed by local scouring and reworking during storm events. Cycles typically comprise a coarse-grained rudstone-to-grainstone lower part that fines upward into a wackestone topped by a cemented firm ground cap. The mud dominated portions of the cycles commonly exhibit vertical variation with zones of different degrees of bioturbation-related fabrics. Cycles are separated by sharp-to-erosional bases of varying relief, which cause cycle thickness to vary laterally, grain dominated portions to pinch out and firm grounds to be locally removed. Locally, 1-3 m thick chaotically bedded conglomeratic intervals occur, produced by larger storm events. These contain overturned clasts up to 1 m in diameter and infill scours with steep-to-vertical walls that incise several meters into underlying deposits and connect coarse-grained facies from different cycles. Storm event deposits vary laterally and vertically in their geometry, spacing and connectivity. Few coarse-grained beds extend across an outcrop (<1 km), but instead pinch out laterally. In combination, these geometric relationships increase vertical connectivity and limit lateral continuity of coarse-grained facies, which presents challenges for characterizing inter-well volumes. Analysis of scour-and-fill geometries shows symmetrical and asymmetrical cross-sectional profiles, implying 3D variation in scour geometry and orientation. These observations were synthesized to develop geometrical templates for fining upward cycles and scours, including their internal variation, such as bioturbation, for implementation in surface-based reservoir models. These templates can be used to test the impact of the observed heterogeneity on the identification and correlation of reservoir flow units using well data, and on the effective properties of the flow units.

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1. Aims

- understand scour development and rudstone deposition
- quantify rudstone-filled scours and related rock property distribution and connectivity
- understand their impact on flow behaviour and productivity

2. Geological context of study dataset

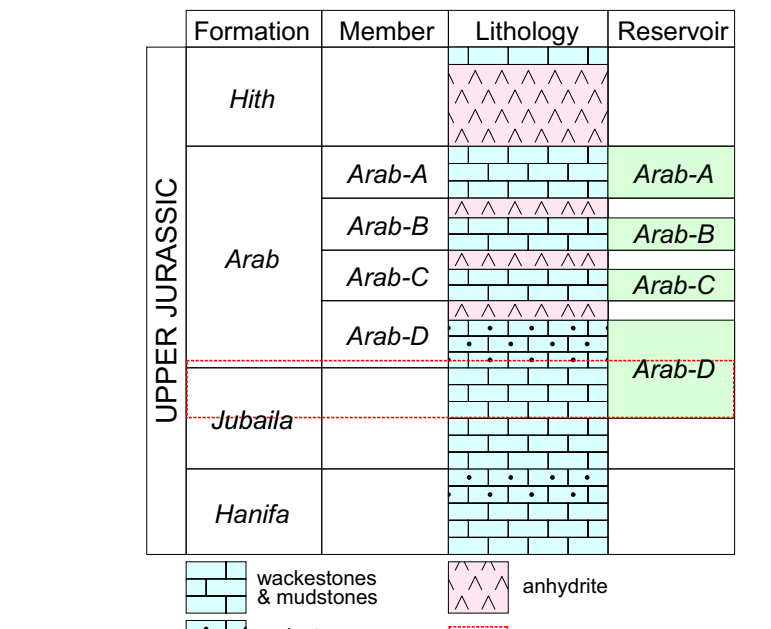


Fig.1 Generalised Upper Jurassic stratigraphy for the Arabian Platform. The interval exposed in the selected outcrops (Arab-D reservoir zones 2B and 3A) is indicated in the red box (modified from Powers, 1968; Meyer et al., 1996).

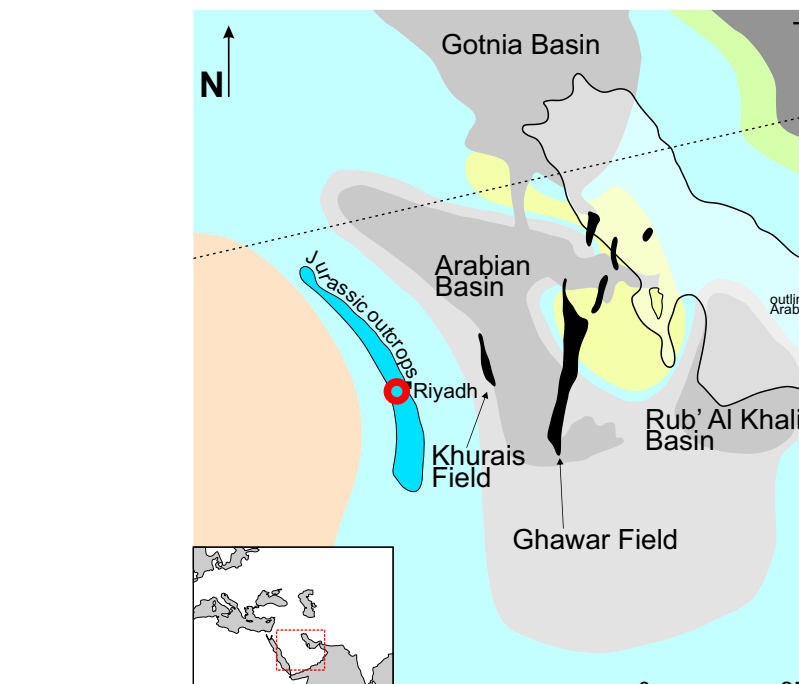


Fig.2 Palaeogeographic map of the Arabian Platform during the late Jurassic (modified from Handford et al., 2002; cf. Lindsay et al., 2014). The location of the studied outcrops is indicated by a red circle, west of Riyadh.

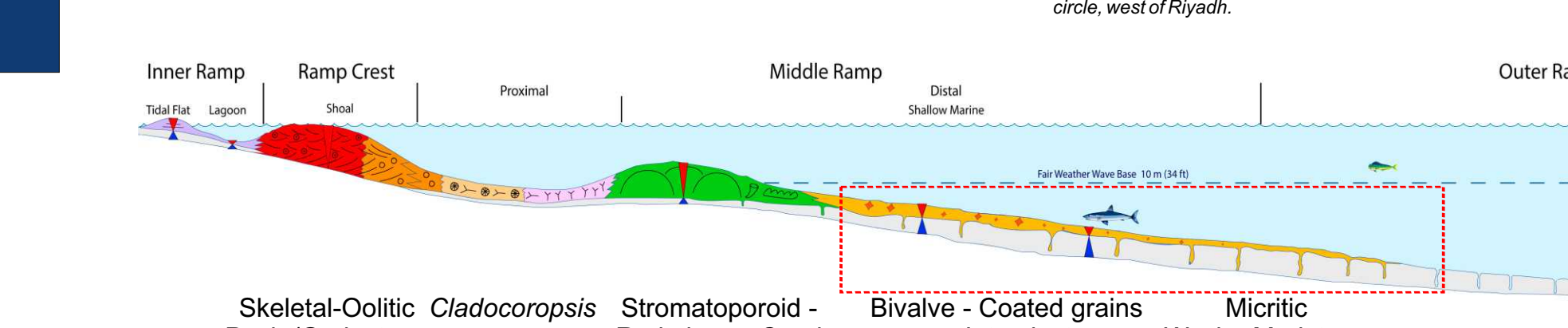


Fig.3 Idealized depositional model of the Arab-D reservoir carbonate ramp in the Ghawar Field, modified from Lindsay et al. (2006) with associated lithofacies classification. The studied outcrops mainly expose deposits of the distal part of the middle ramp and the outer ramp (red box).

3. Correlation challenge

- 4 closely spaced logs (50-200m)
- correlation of rudstone units is often not possible
- coarse-grained units pinch out laterally
- in strike-section scours only improve lateral connectivity slightly

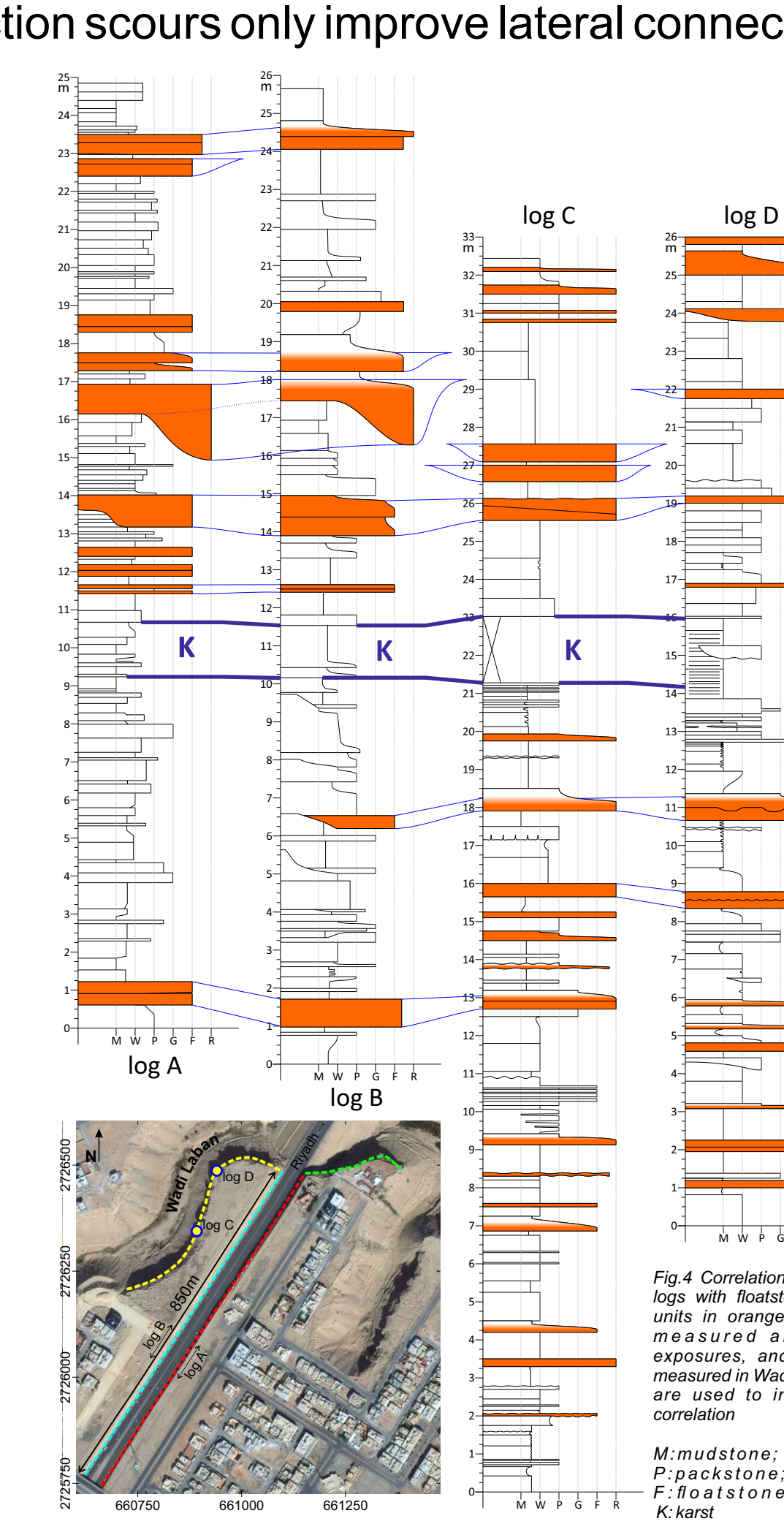


Fig.4 Correlation of 4 sedimentary logs with floatstone and rudstone units in orange. Logs A-B were measured along road-cut exposures, and logs C-D were measured in Wadi Laban. Blue lines are used to indicate potential correlation

M: mudstone; W: wackestone
P: packstone; G: grainstone
F: floatstone; R: rudstone
K: karst

4. Dataset and methods

- 800m long road cuts and neighbouring wadis (Fig.5)
- 3D digital outcrop model at ~2cm resolution (Fig.6)
- 4 sedimentary logs (Fig.4)
- surface-based modelling method
- unstructured time-adaptive-mesh flow simulator

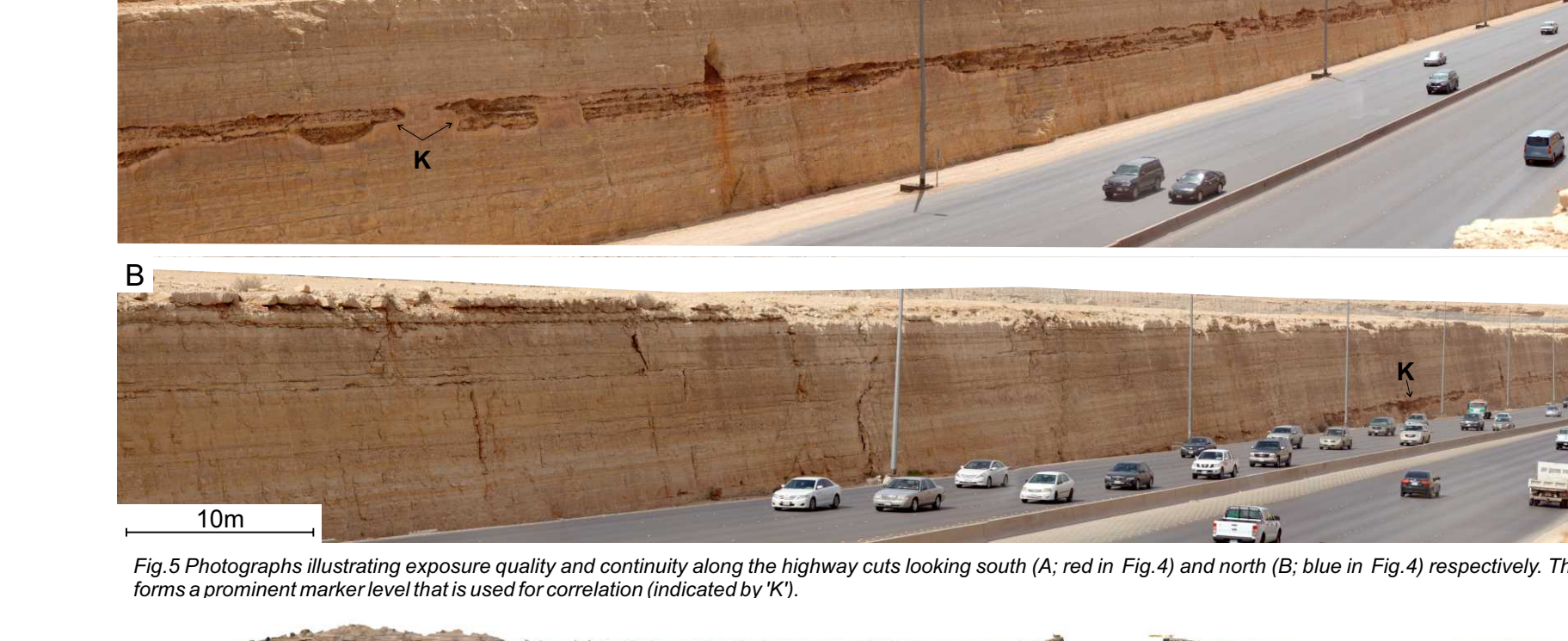


Fig.5 Photographs illustrating exposure quality and continuity along the highway cuts looking south (A; red in Fig.4) and north (B; blue in Fig.4) respectively. The karstified interval forms a prominent marker level that is used for correlation (indicated by 'K').

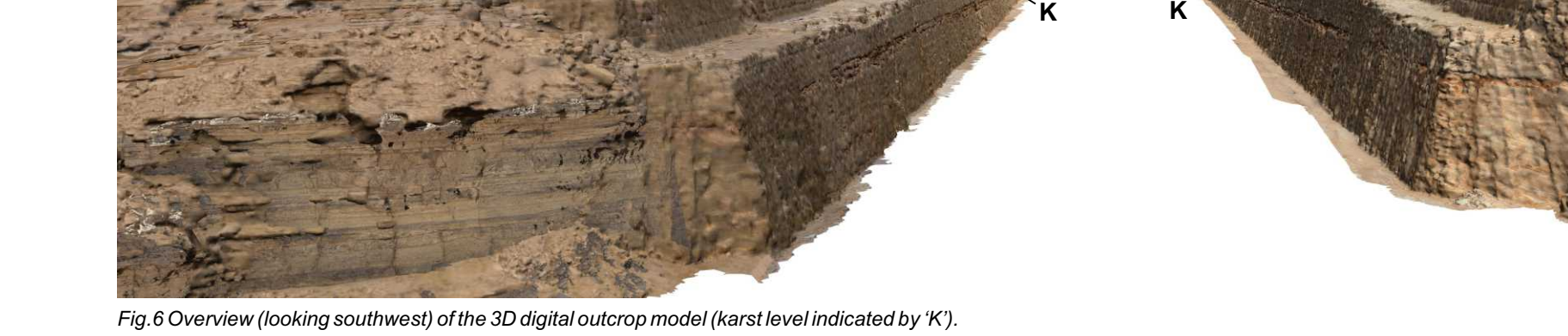


Fig.6 Overview (looking southwest) of the 3D digital outcrop model (karst level indicated by 'K').

5. Outcrop observations

5.1 Rudstone-filled scours

- scours have steep-to-vertical walls that incise several metres into underlying deposits
- infilled by 1-3 m thick chaotically bedded conglomeratic intervals
- conglomerate includes overturned stromatoporoid and coral clasts of up to 1 m in diameter
- formed during large storm events which produced steep-sided scours
- conglomeratic debris transported offshore from shallower water settings by debris or hyperconcentrated density flows, strengthened by relaxation current

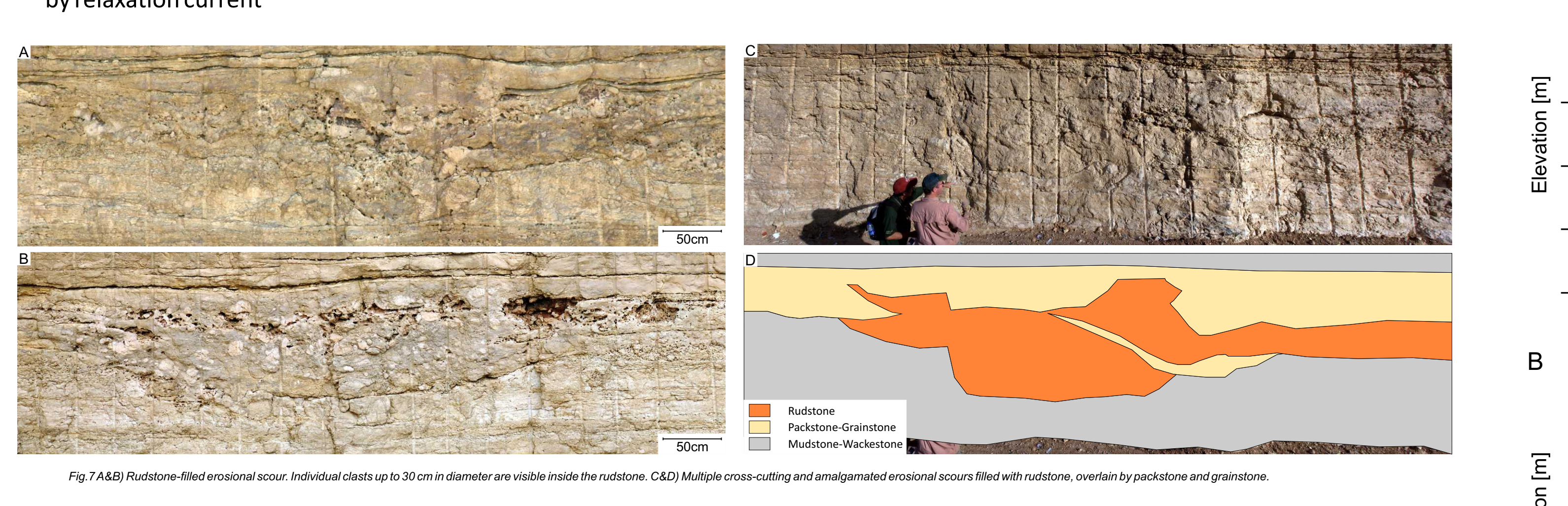


Fig.7 A&B) Rudstone-filled erosional scour. Individual clasts up to 30 cm in diameter are visible inside the rudstone. C&D) Multiple cross-cutting and amalgamated erosional scours filled with rudstone, overlain by packstone and grainstone.

5.2 Fining-upward cycles

- series of thin (0.5-1 m) fining-upward cycles
- sharp-to-erosional bases of varying relief
- pack-grainstone base
- bioturbated wacke-stone centre
- firmground tops
- storm events that locally scoured and reworked sediments

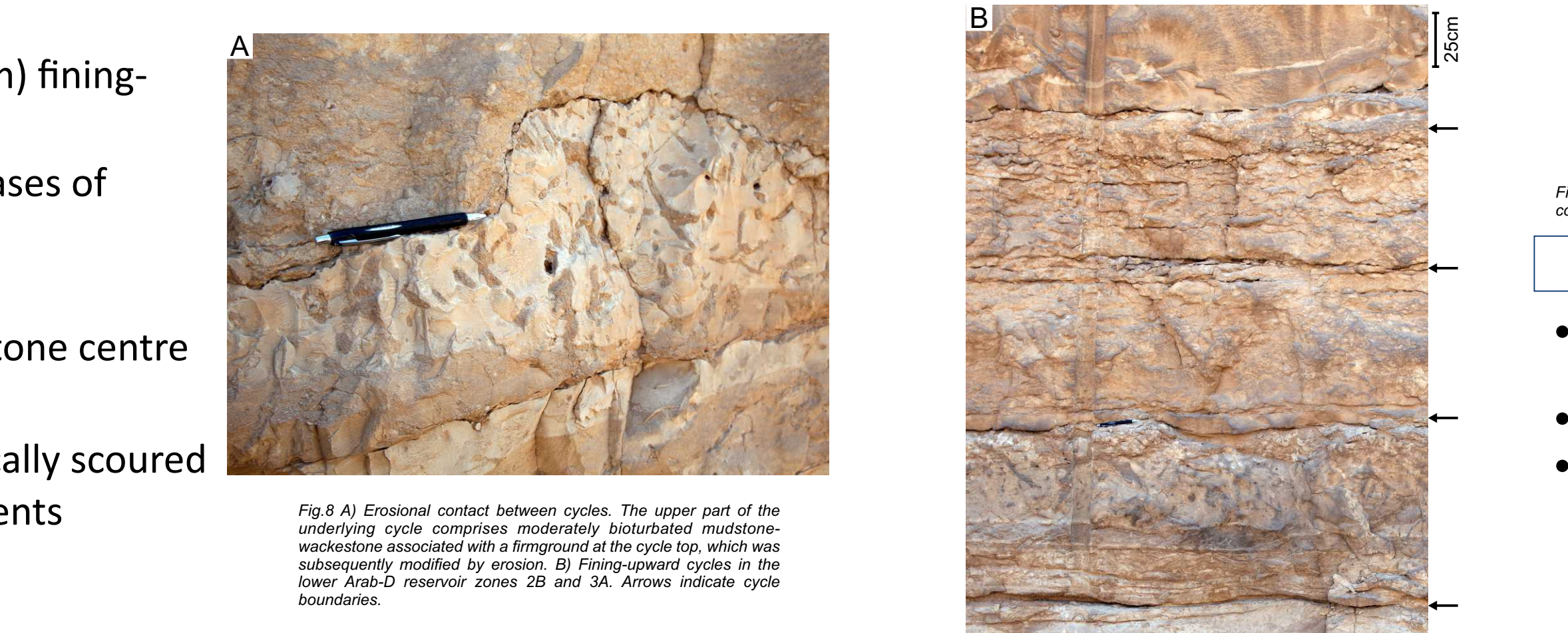


Fig.8 A) Erosional contact between cycles. The upper part of the underlying cycle comprises moderately bioturbated mudstone-wackestone associated with a firmground at the cycle top, which was subsequently modified by erosion. B) Fining-upward cycles in the lower Arab-D reservoir zones 2B and 3A. Arrows indicate cycle boundaries.

6. Quantitative characterization of stratigraphic architecture

6.1 Rudstone tracing

- basal surfaces of rudstone-filled scours are traced along outcrops (Fig.9; +/- 7000m traced)
- scours typically have a shallow portion (scour wings), locally interrupted by deeper scour pits or resistant ridges
- scour wings are important for lateral connectivity
- scour pits improve vertical connectivity to underlying fining-upwards cycles and rudstones

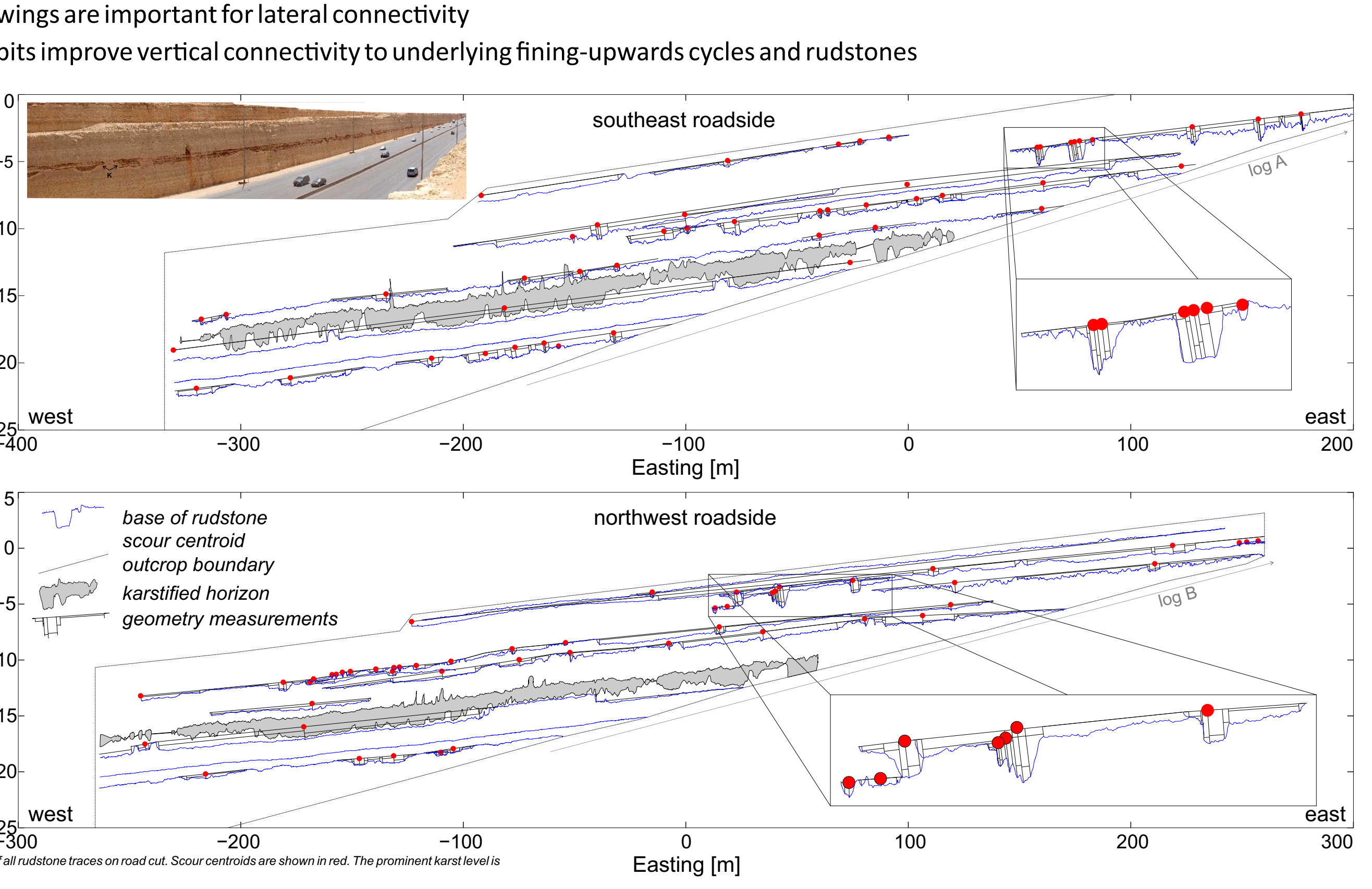


Fig.9 Overview of all rudstone traces on road cut. Scour centroids are shown in red. The prominent karst level is coloured in grey.

6.2 Lateral scour spacing

- absence of strong patterns in the distribution of scours (Fig.10)
- no dominant control on their lateral spacing
- weak clustering on the NW side (Fig.10B) likely reflects re-occupation of existing scours or a localised palaeobathymetric low

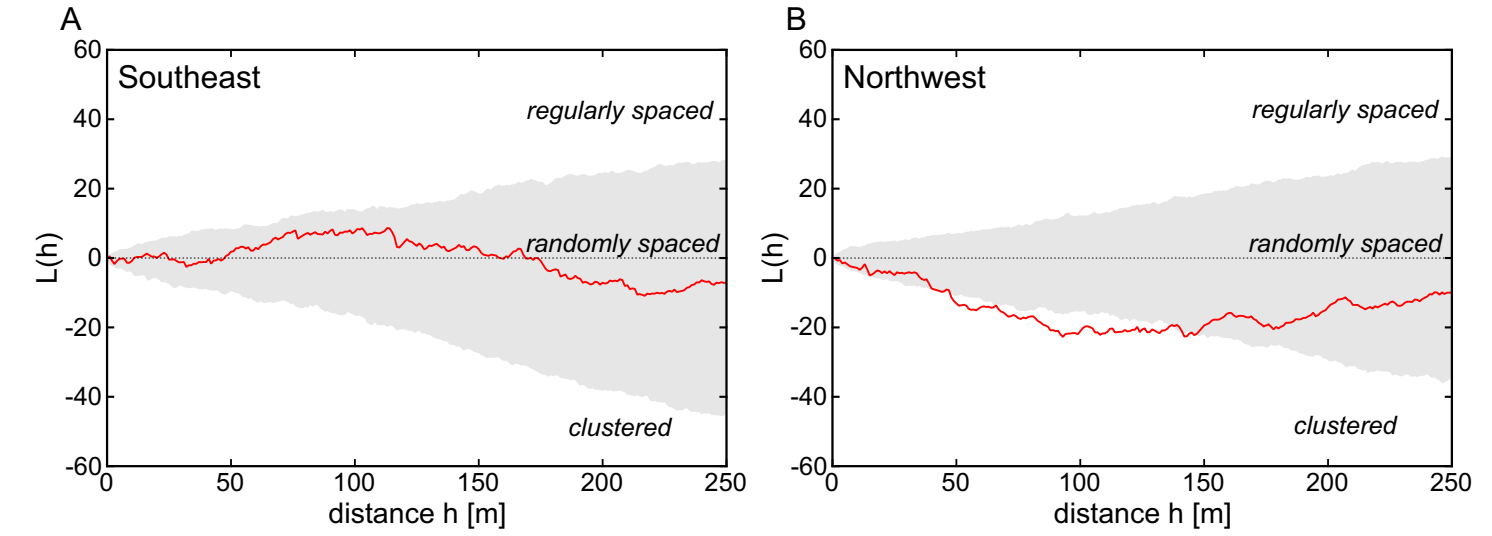


Fig.10 Besag's L-function for scour-pit centroids on the (A) SE and (B) NW sides of the road section.

6.3 Cross section template

- scour cross sections depths are symmetrical and strong correlation exists between scour pits and wings
- no change in scour process or boundary conditions between flows or along scour trajectory
- asymmetry of scour pit flanks indicates consistent curvature of scour trajectory
- most scours cut through at least one fining-upwards cycle, improving vertical connectivity

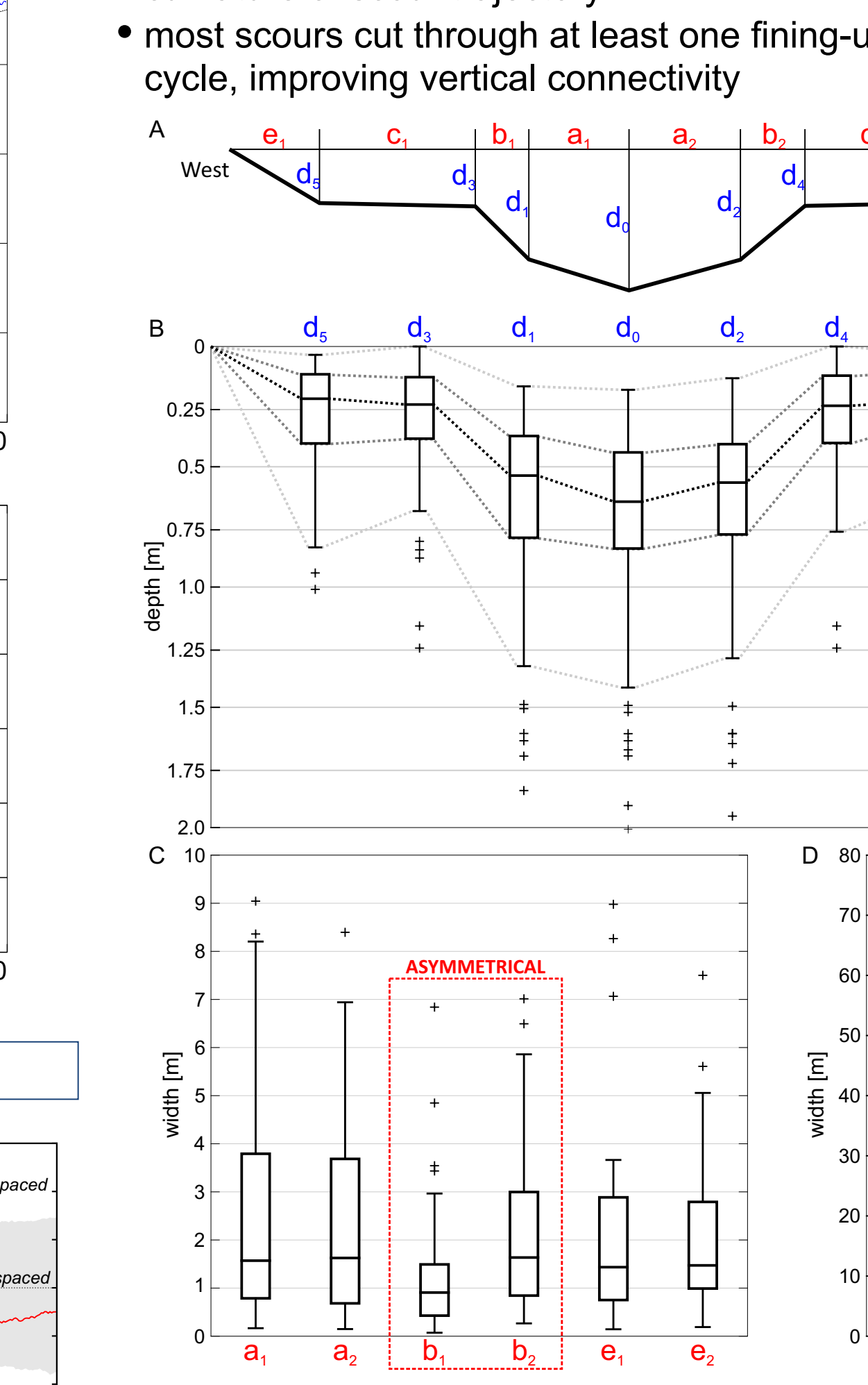


Fig.11 Overview of measurements that are used to characterise the cross-sectional geometry of the erosional bases of scours. A) Conceptual cross section of a scour surface, with 15 parameters defining its shape. B) Box plots of scour depth measurements. C-D) Box plots of scour width measurements. The total number of measurements is 43-77 for different parameters.

6.4 Scour orientation

- N-S trend of the scours (Fig.12) is not consistent with an W-E onshore-to-offshore direction in the interpreted regional palaeogeographic context (Fig.2)
- local bathymetry must have deflected flow consistently to a N-S orientation
- more geometrical data is needed to understand N-S scour continuity

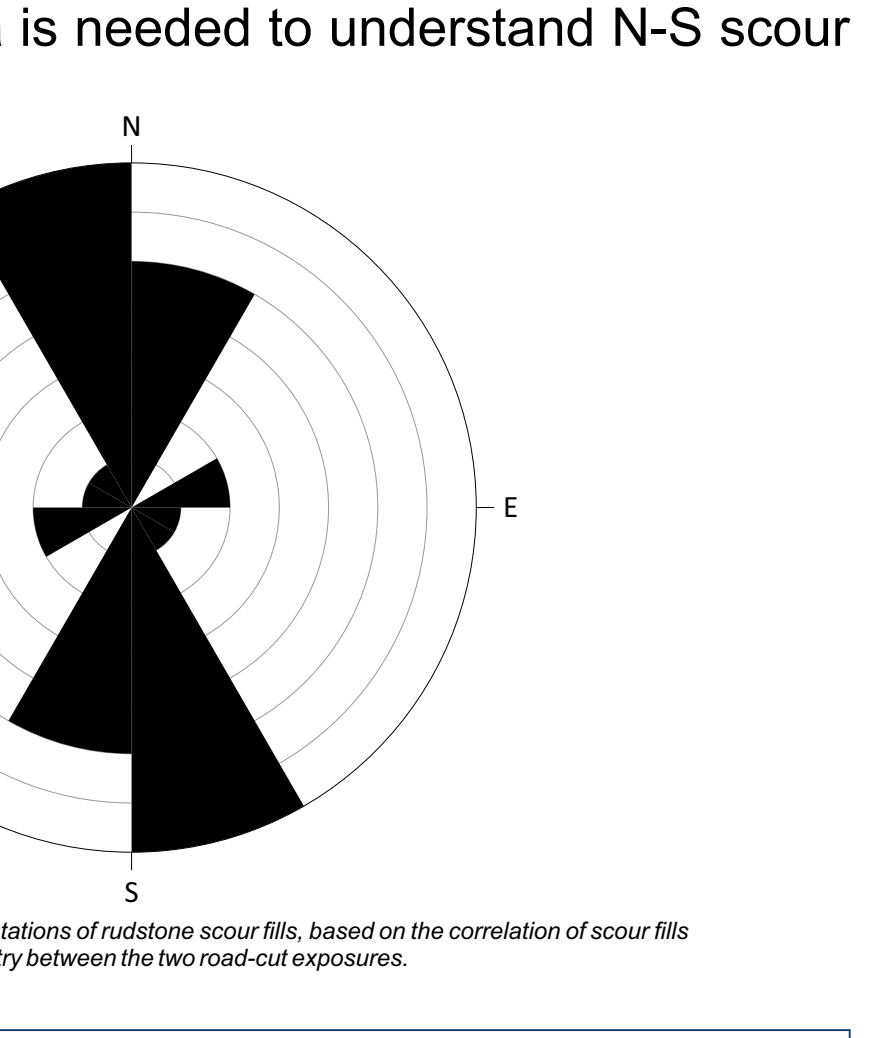


Fig.12 Rose diagram of the orientations of rudstone scour fills, based on the correlation of scour fills of similar cross-sectional geometry between the two road-cut exposures.

6.5 Dimension correlation

- moderate to strong correlations between successive depth parameters
- no correlation was observed between width measurements

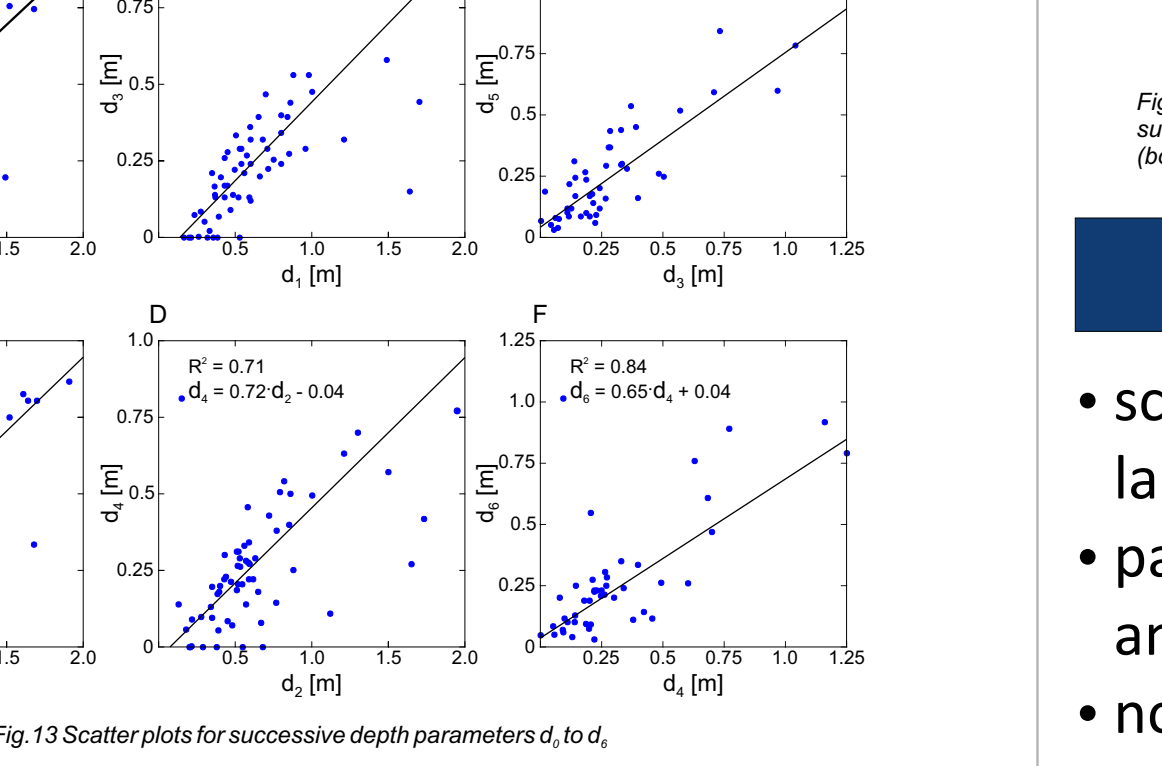
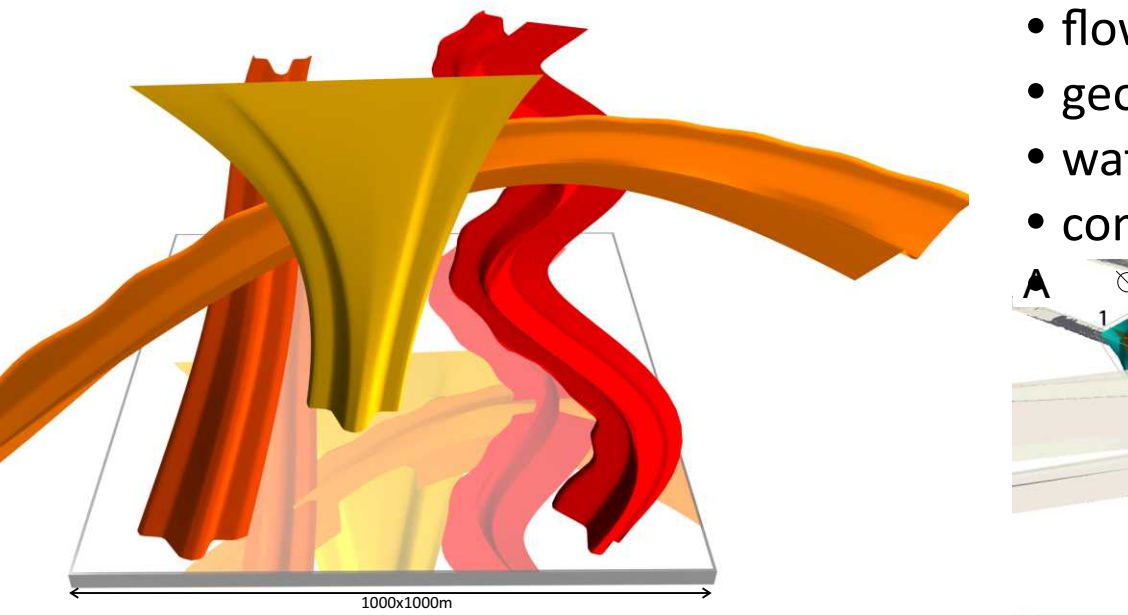


Fig.13 Scatter plots for successive depth parameters d_0 to d_6

7. Surface-based modelling of scours & cycles

- NURBS (Non-Uniform Rational B-Splines) are used to model the scour geometries
- flexible and efficient approach to produce complex smooth geometries
- cross sections, generated using outcrop statistics (Fig.10-13), are extruded along a trajectory to form a surface (Fig.14A)
- outcrops can be used to condition the location and shape of scours (Fig.14B)



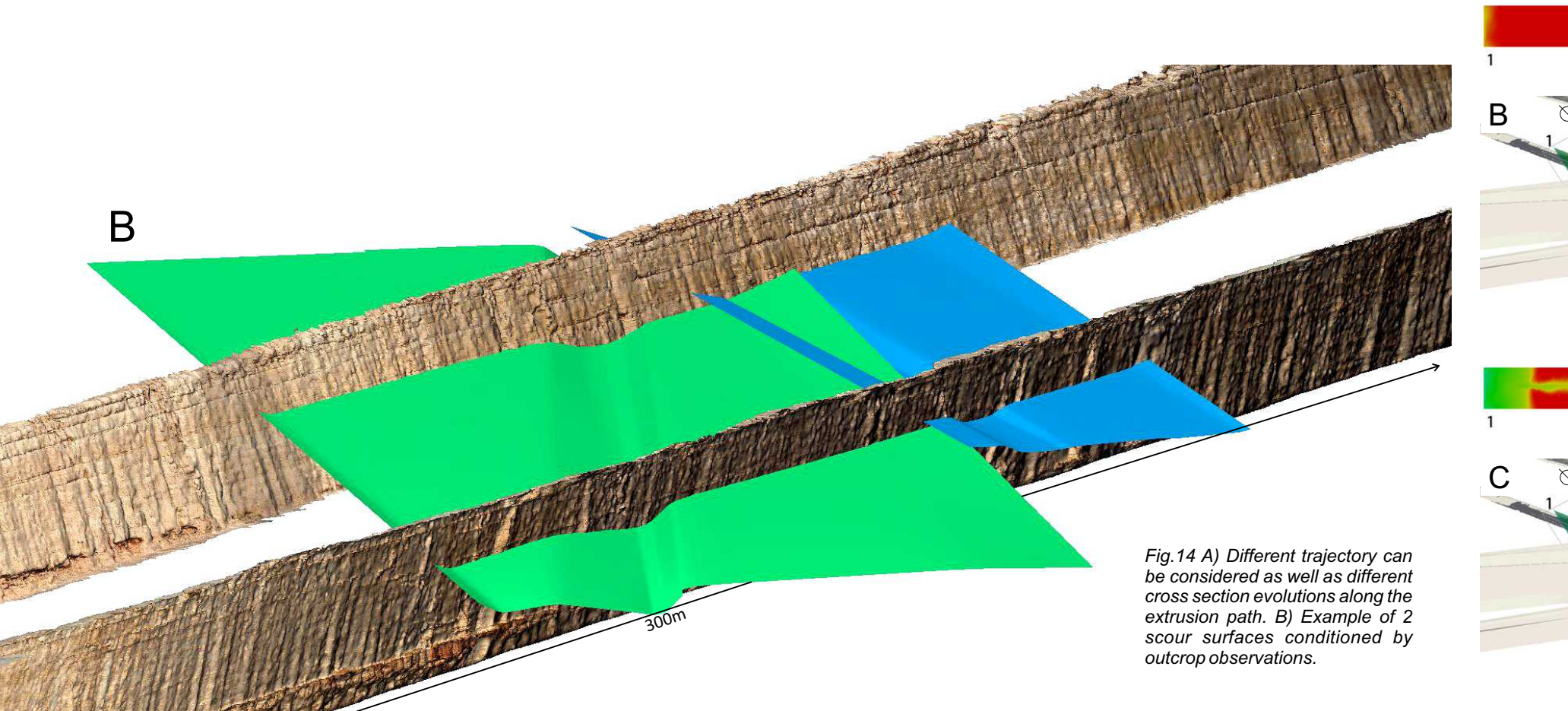


Fig.14 A) Different trajectory can be considered as well as different cross section evolutions along the extrusion path. B) Example of 2 scour surfaces conditioned by outcrop observations.

- cycles show variable lateral thickness changes due to (1) incision by the overlying cycles and (2) lateral depositional variations
- cycles' base, top and internal surfaces can be represented by NURBS-surfaces (Fig.15A-B)
- surfaces can be combined to produce a realistic cycle stack. Scour surfaces are then stacked on cycle surfaces

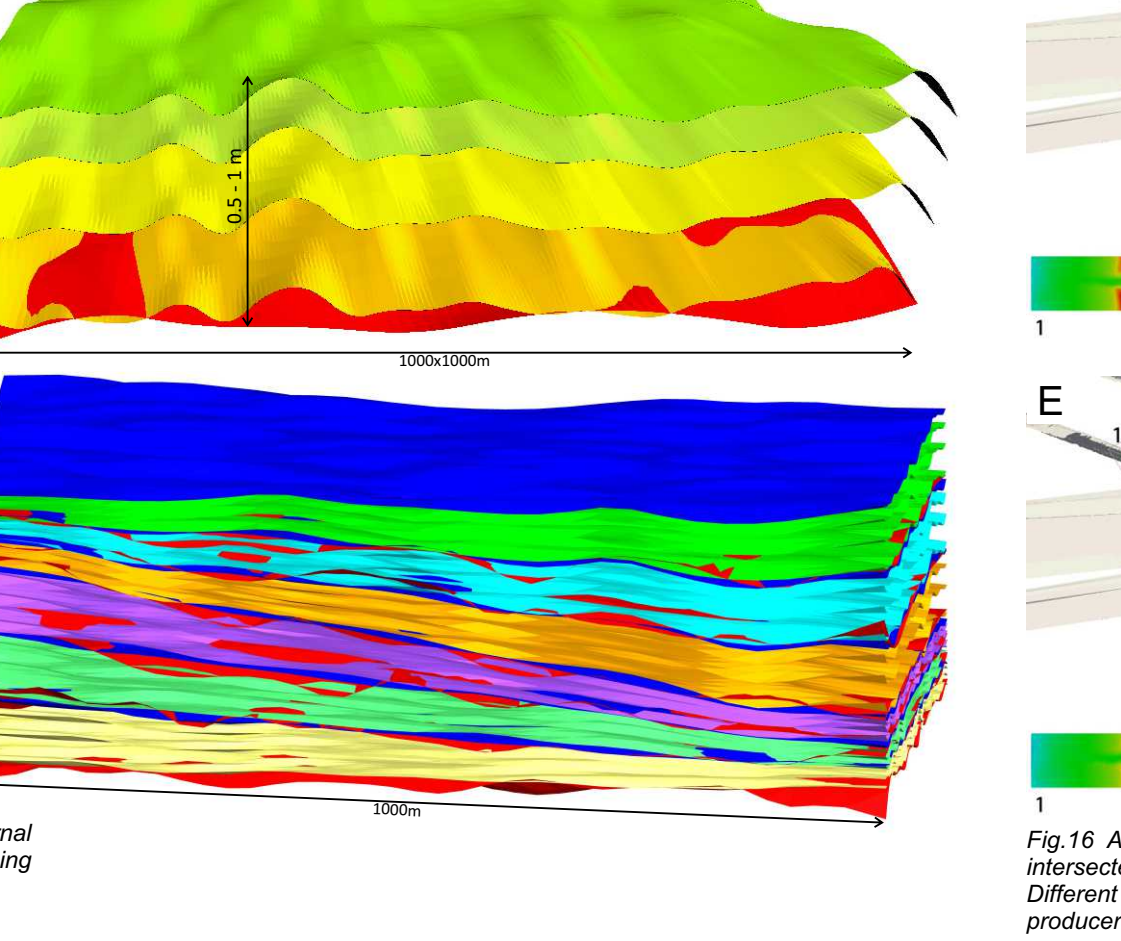


Fig.15 A) Example of a fining-upwards cycle consisting of cycle base (red), cycle top (green) and 3 internal surfaces (yellow-green) bounding intra-cycle petrophysical variability. B) Stacking of 6 cycles thinning (bottom 3) and thickening (top 3) towards right (base surfaces: red, top surface: blue).

8. Complex flow behaviour

- flow simulation of surface-based models
- geometry and connectivity are preserved by time-adaptive unstructured mesh
- waterflooding experiment of scours conditioned by outcrop observations (Fig.8C-D & Fig.16B)
- complex patterns emerges that shows how rudstone scours and their intersection impacts flow

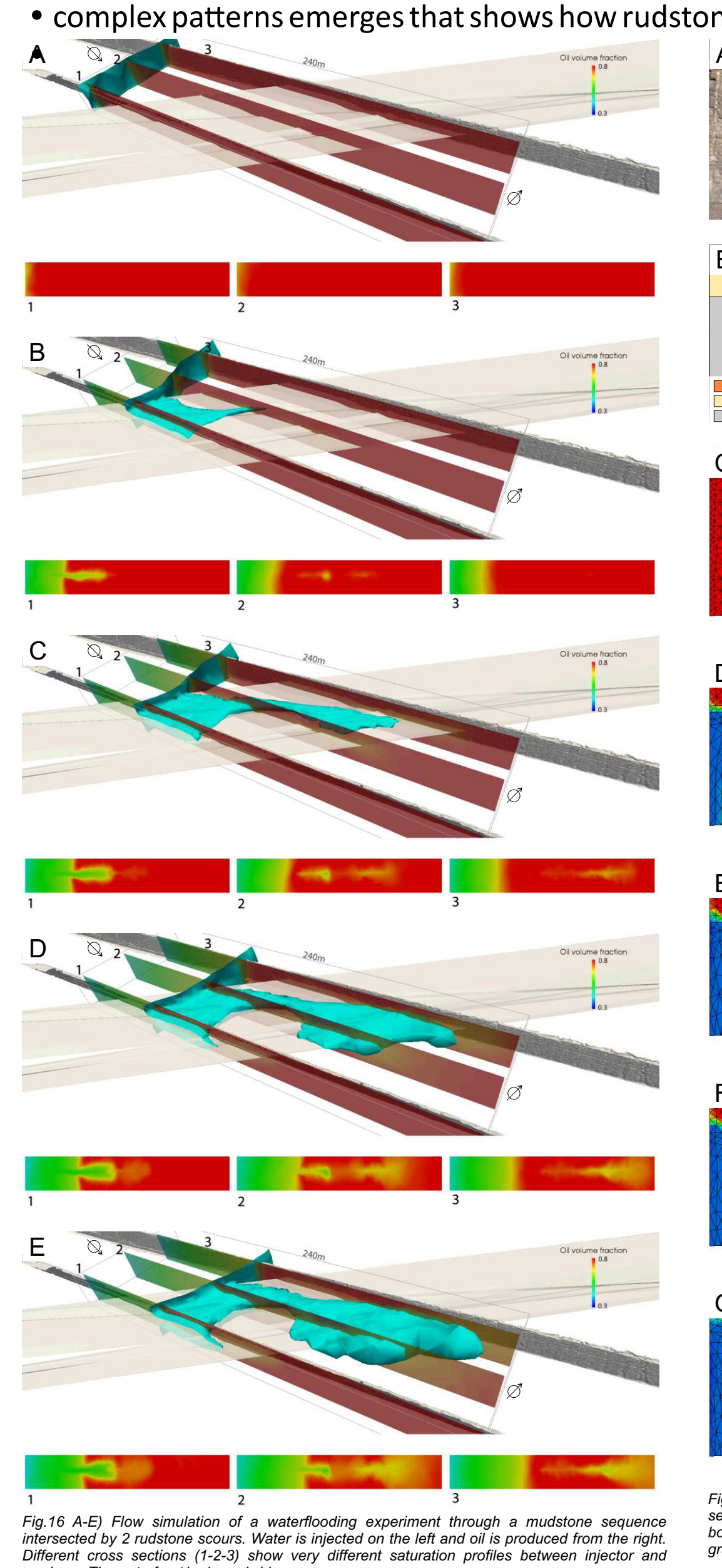


Fig.16 A-E) Flow simulation of a waterflooding experiment through a mudstone sequence intersected by 2 rudstone scours. Water is injected on the left and oil is produced from the right. Different cross sections (1-2-3) show very different saturation profiles between injector and producer. The waterfront is shown in blue.

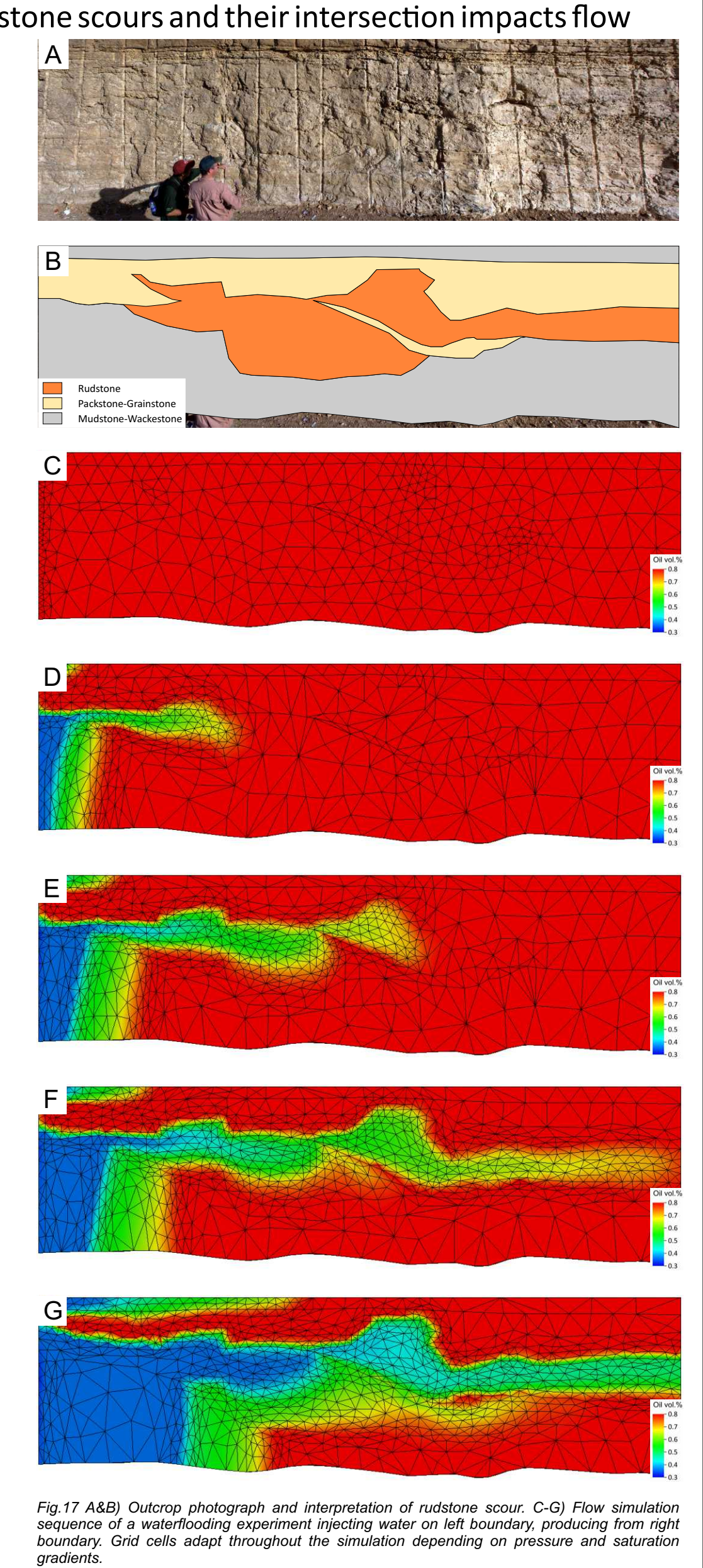


Fig.17 A&B) Outcrop photograph and interpretation of rudstone scour. C-G) Flow simulation sequence of a waterflooding experiment injecting water on left boundary, producing from right boundary. Grid cells adapt throughout the simulation depending on pressure and saturation gradients.

9. Conclusions

- scouring and rudstone deposition are the result of large storm events
- palaeobathymetry controlled scouring trajectories and thus rudstone distribution
- non-layercake correlation, even at 100s meter scale
- scour wings improve lateral connectivity
- scour pits improve connectivity with underlying cycles and rudstone units
- surface-based modelling and simulation preserves complex geometries throughout

10. References

Handford, C.R., Cantrell, D.L. and Keith, T.H. (2002) Regional facies relationships and sequence stratigraphy of a supergiant reservoir (Arab-D member), Saudi Arabia. In: Sequence stratigraphic models for exploration and production: Evolving methodology, emerging models and application histories, 22nd Annual Bob F. Perkins Research Conference: Gulf Coast Section, pp. 539-564. SEPM.

Lindsay, R.F., Cantrell, D.L., Hughes, G.W., Keith, T.H., Mueller, H.W. and Russell, S.D. (2006) Ghawar Arab-D reservoir: Widespread porosity in shoaling-upward carbonate cycles, Saudi Arabia. In: Giant hydrocarbon reservoirs of the world: From rocks to reservoir characterization and modeling (Eds P.M. Harris and L.J. Weber), AAPG Memoir, 88, pp. 97-137.

Lindsay, R.F. (2014) Rediscovering the Arab-D reservoir: the search for stratigraphic traps. In: AAPG Annual Convention and Exhibition. AAPG, Houston.

Meyer, F.O., Price, R.C., Al-Ghamdi, I.A., Al-Goba, I.M., Al-Raimi, S.M. and Cole, J.C. (1996) Sequential stratigraphy of outcropping strata equivalent to Arab-D reservoir, Wadi Nisah, Saudi Arabia. GeoArabia, 1, 435-455.

Powers, R.W. 1968. Lexique Stratigraphique International: Saudi Arabia, Centre National de la Recherche Scientifique, Paris.