

PFC2D modelling of sinkhole clusters in karstic depressions

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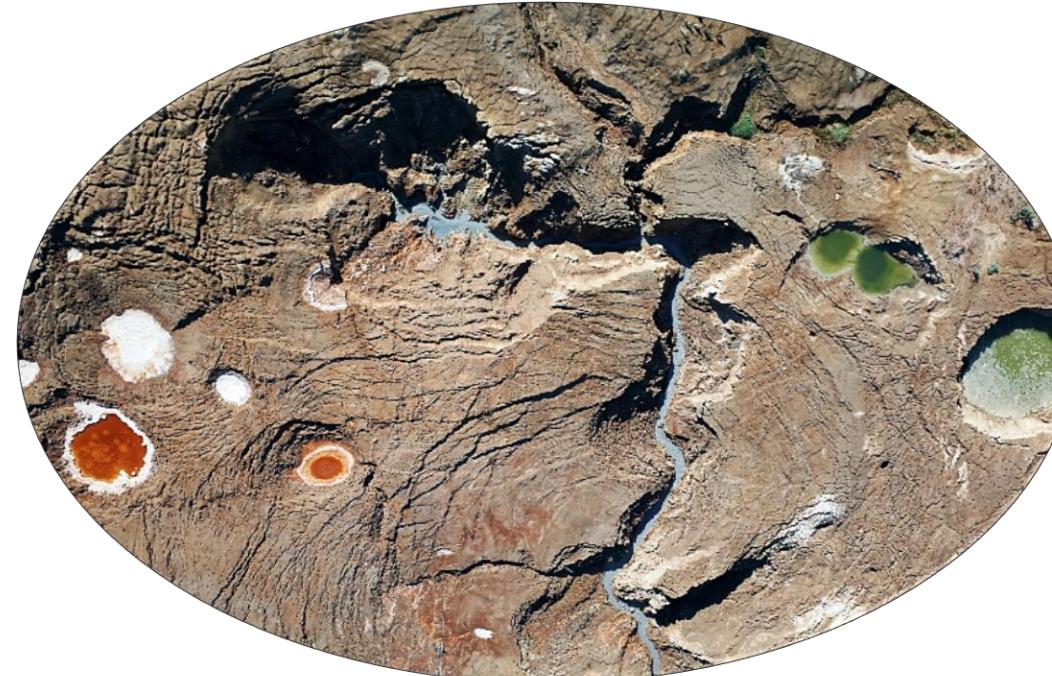
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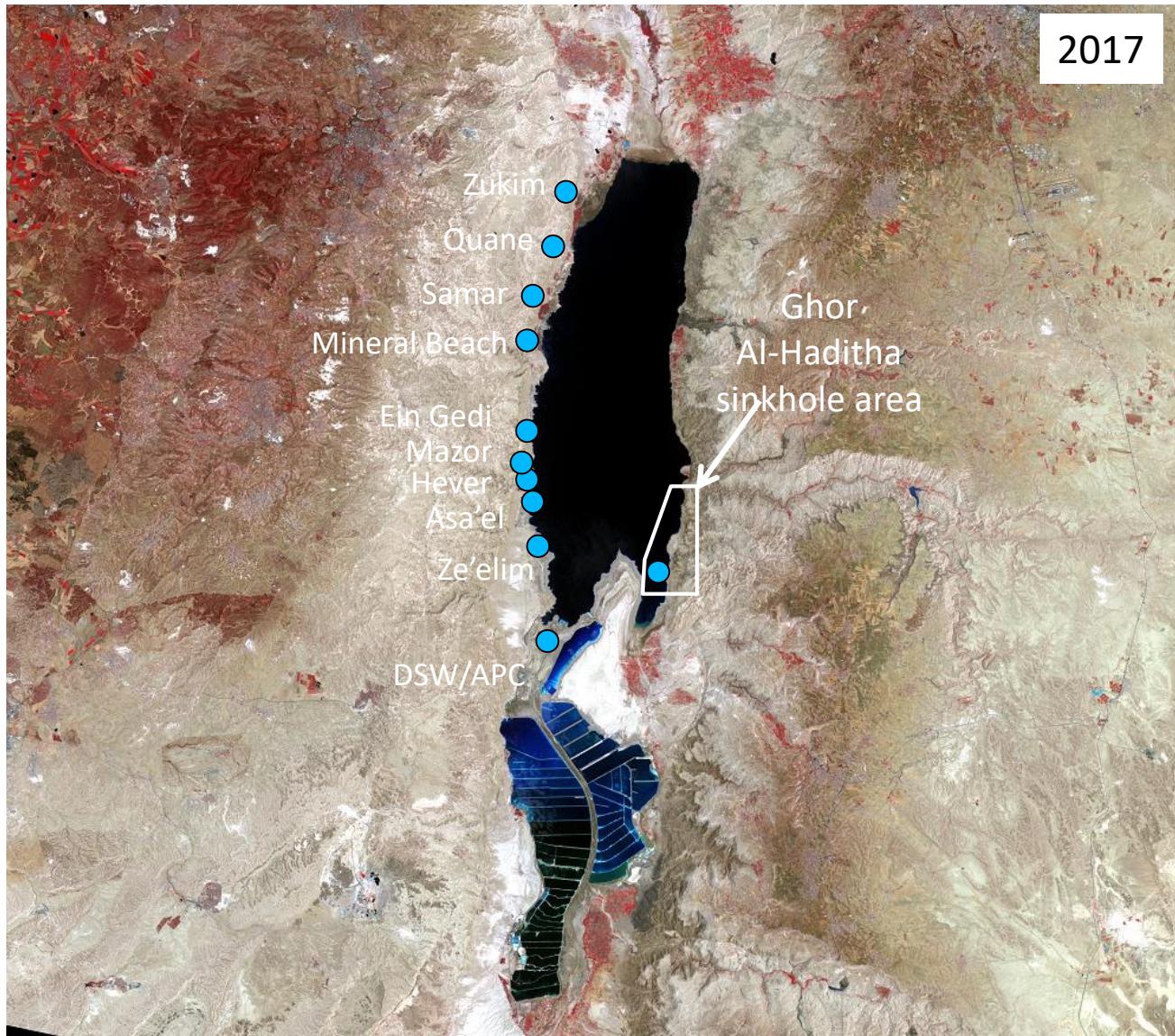
Sinkholes in general

Sinkholes are enclosed depressions of the surface and appear in terrain prone to dissolution and subrosion, like limestone or salt karst.



Sinkholes at the Dead Sea

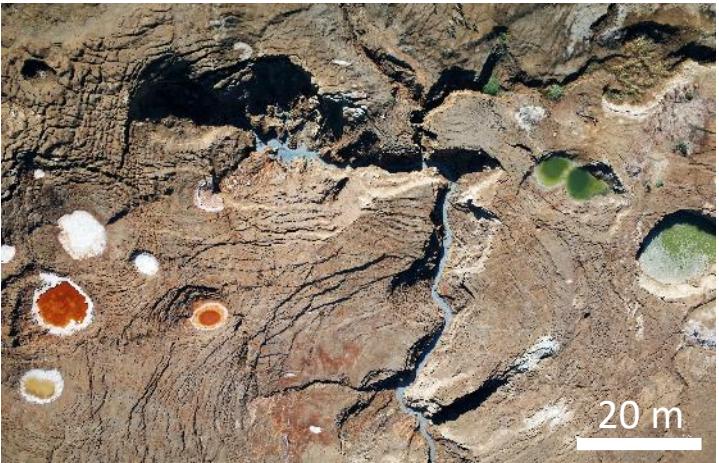
Shrinking of the lake



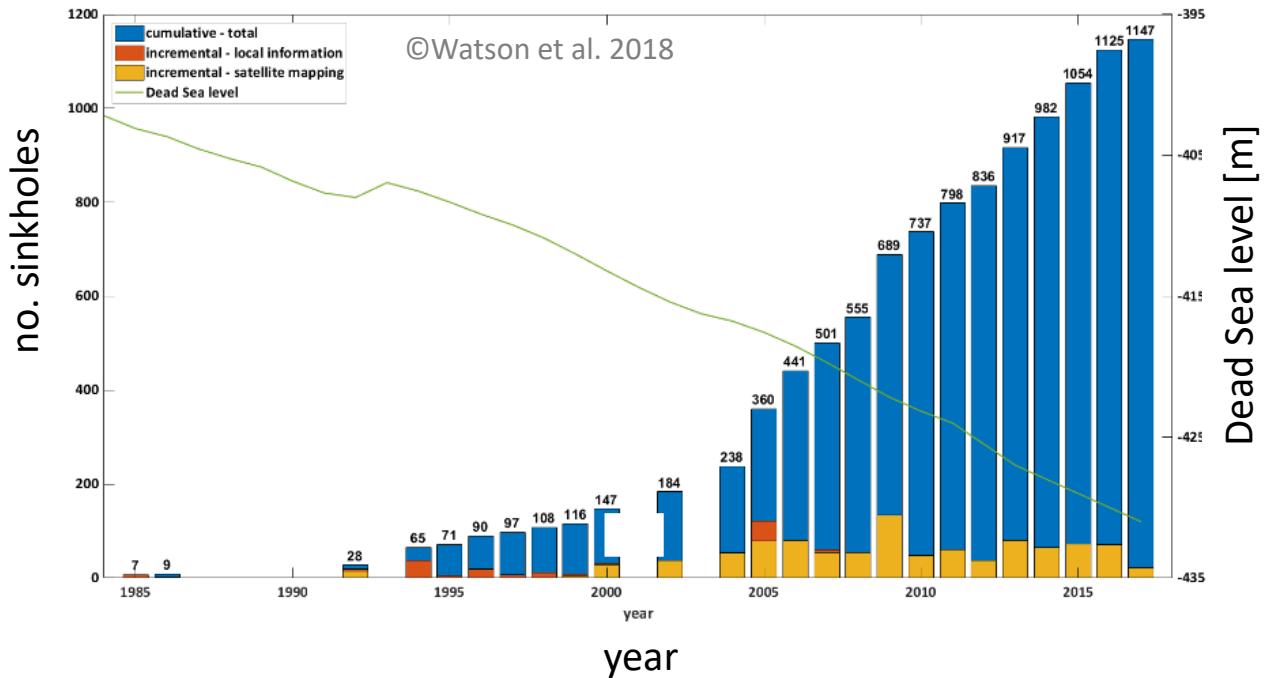
Sinkholes at the Dead Sea

Ghor Al-Haditha

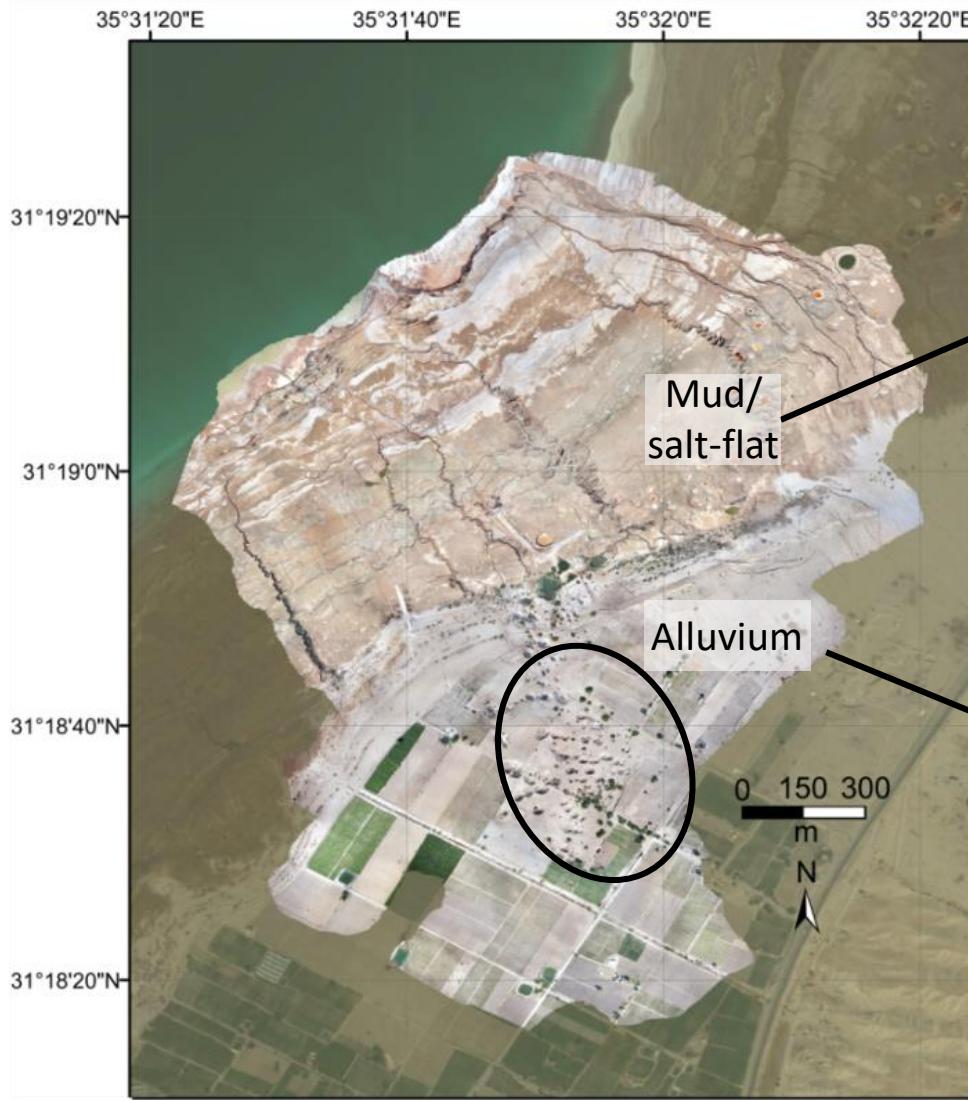
Aerial photographs



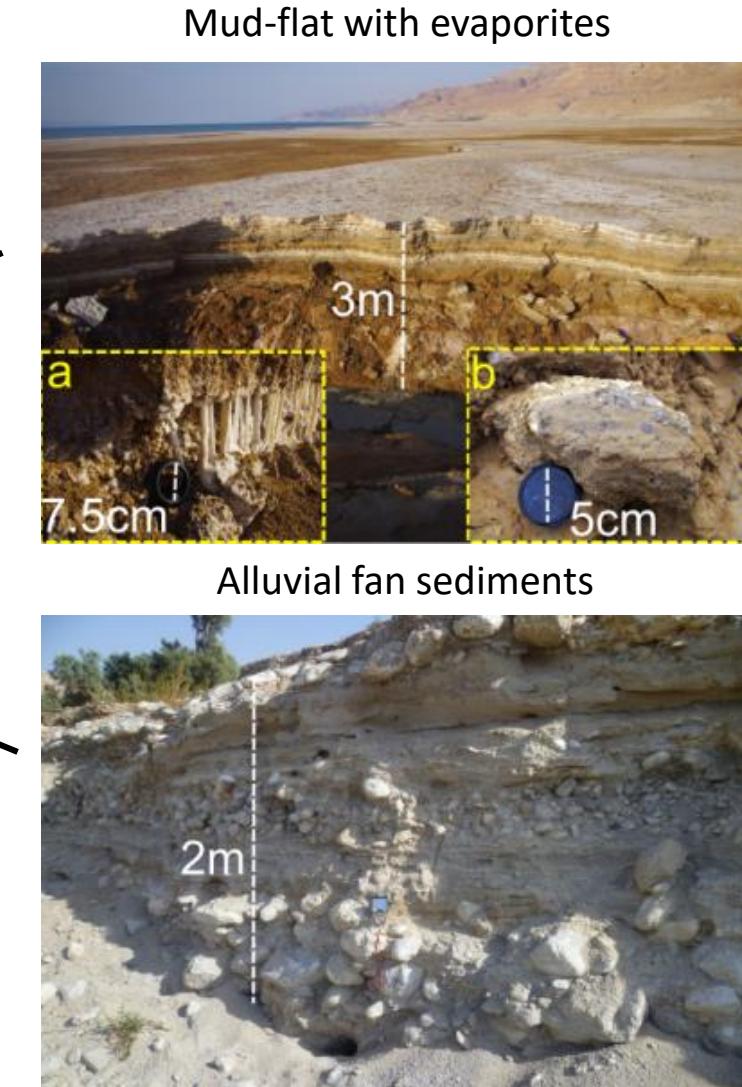
Sinkhole formation rate



Photogrammetry and field analysis



Orthophoto 2014 on satellite image 2011

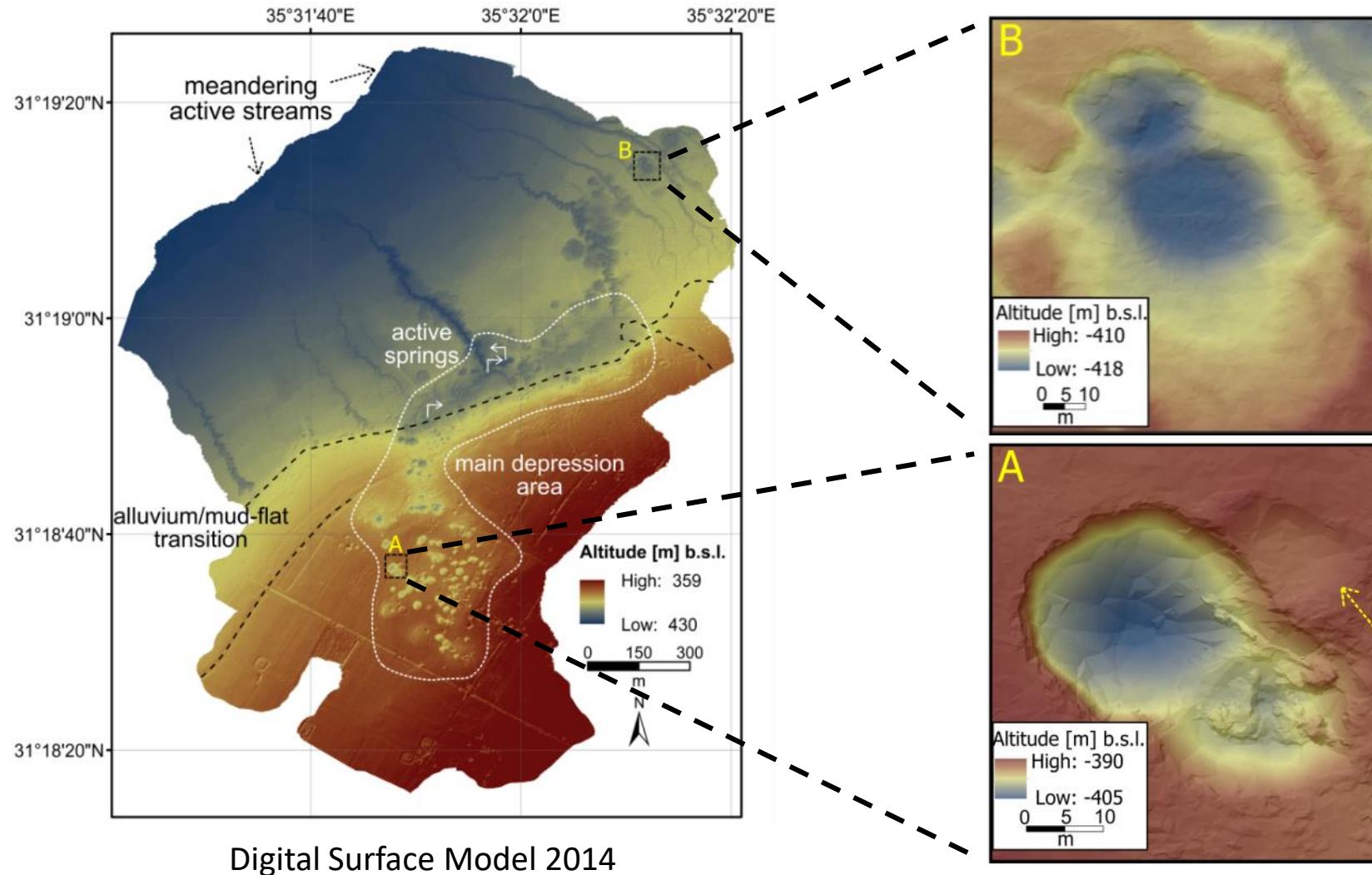


Photogrammetry and field analysis

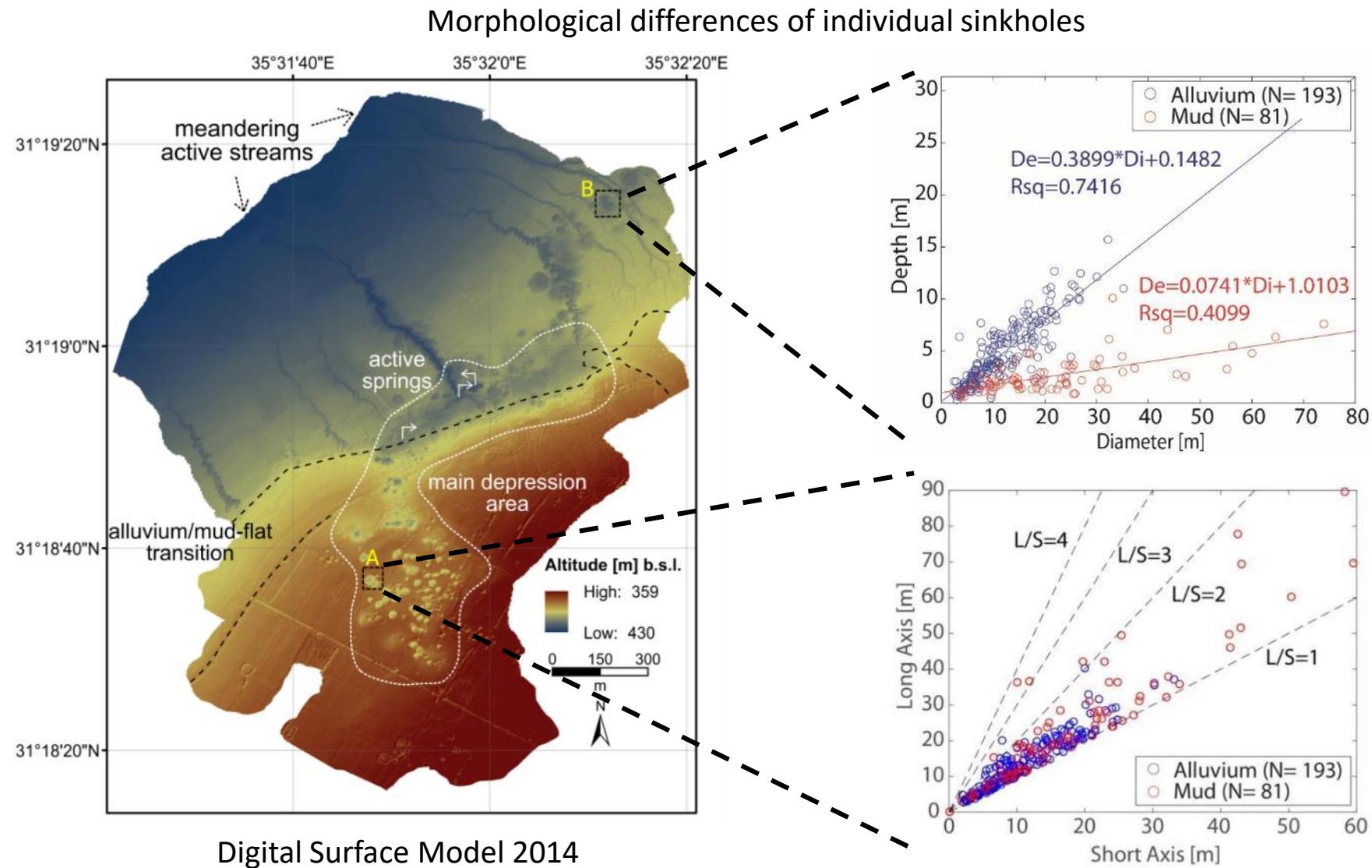


Photogrammetry and field analysis

Morphological differences of individual sinkholes

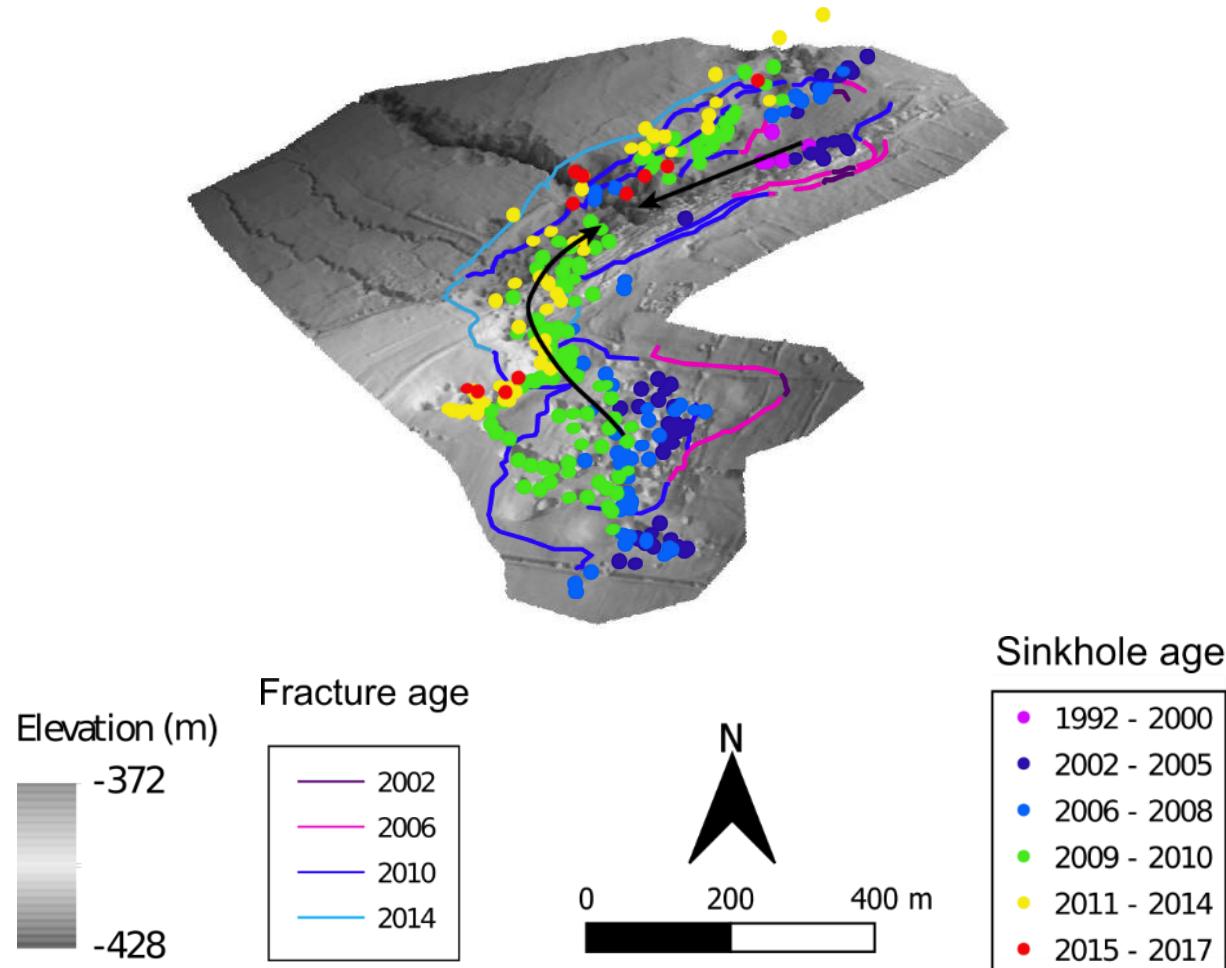


Photogrammetry and field analysis



Photogrammetry and field analysis

Sinkhole clusters and large-scale depressions



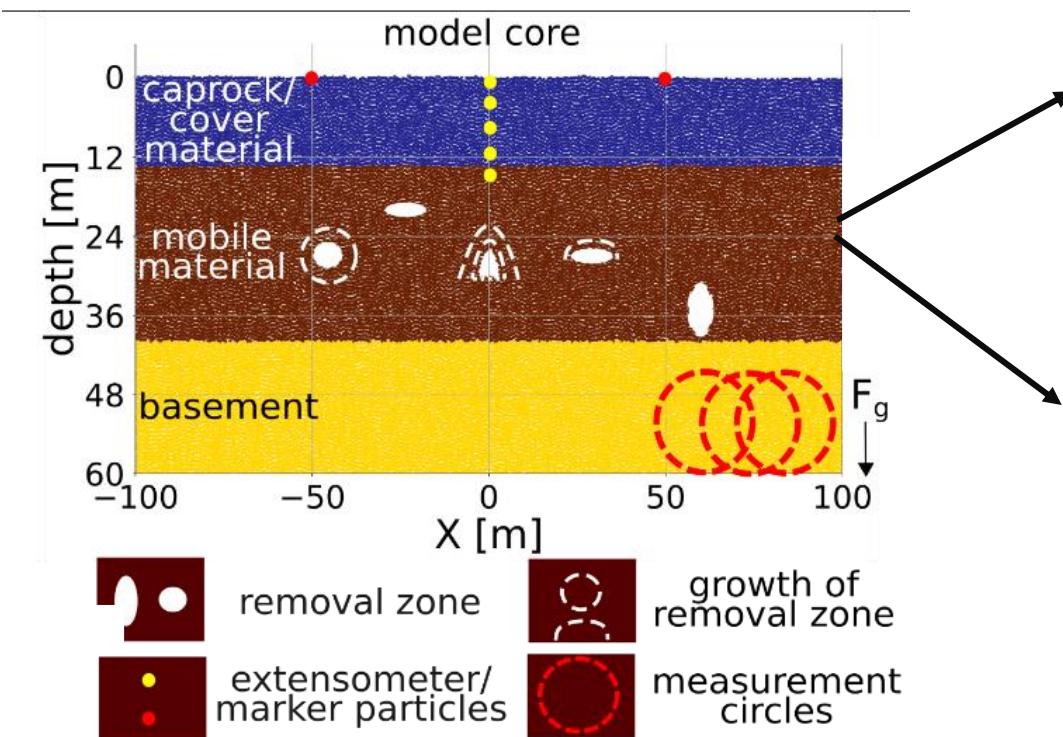
Mod. after Watson et al. 2018

Distinct Element Modelling

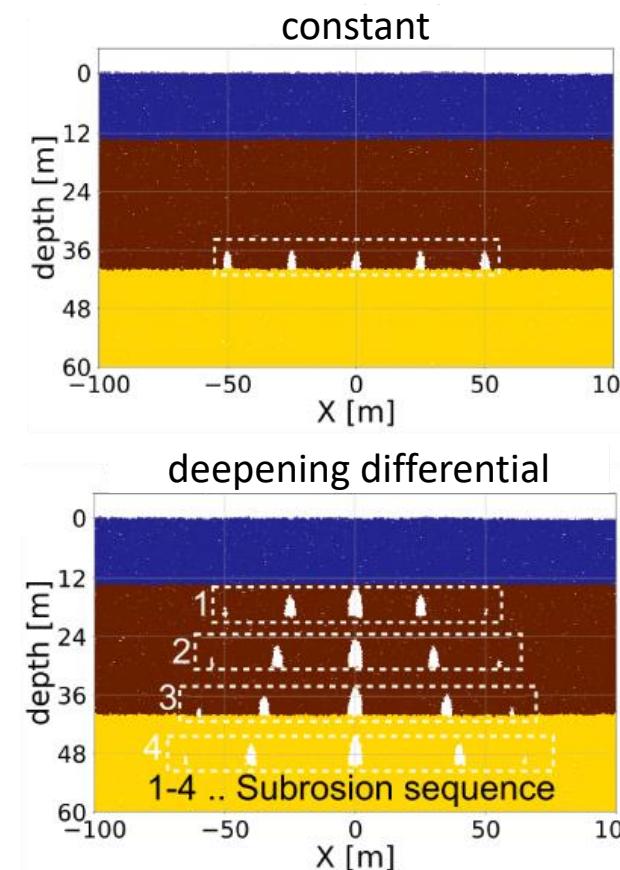
Sinkhole modelling approach

Modelling setup with PFC2D-V5

Model resolution: H = 400 m, W = 400 m, R = 0.32 m



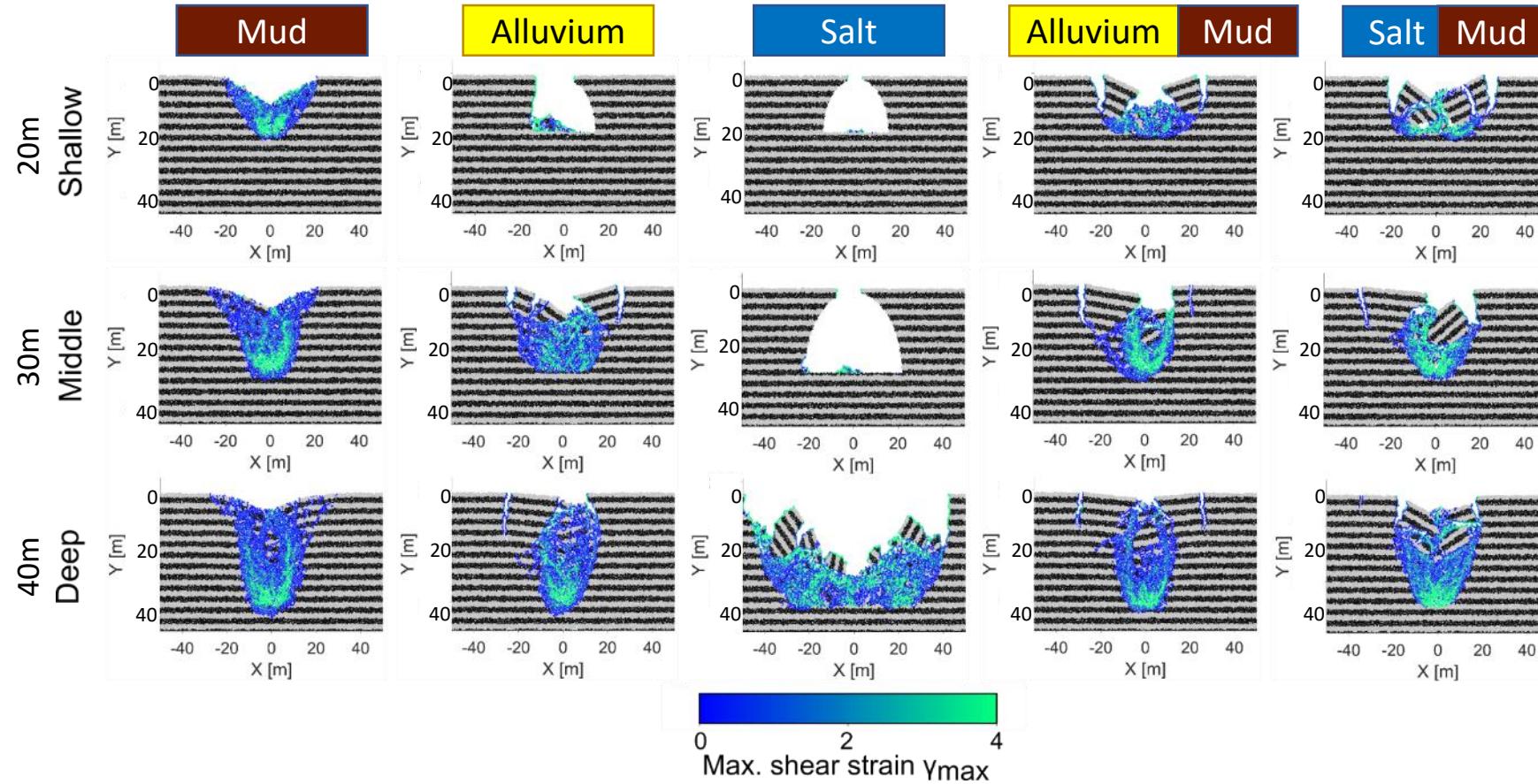
Subrosion procedures



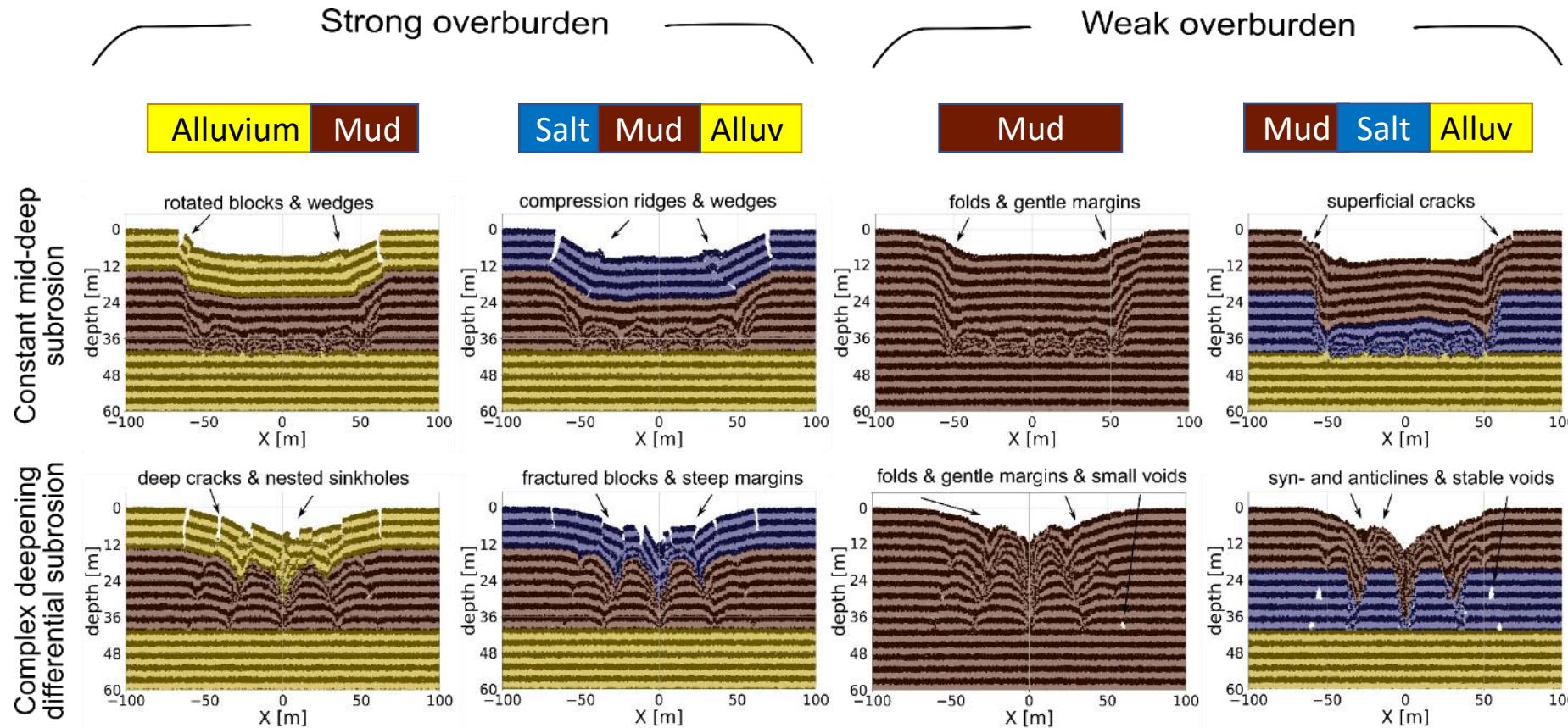
Material parameters

	UCS (-)	UTS	Modulus
Salt	1.23-1.54 MPa	0.31-0.43 MPa	1106 +- 126 MPa
Alluvium	0.52-0.92 MPa	0.18-0.24 MPa	174 +- 25 MPa
Mud	0.06-0.25 MPa	0.01-0.2 MPa	84 +- 20 MPa

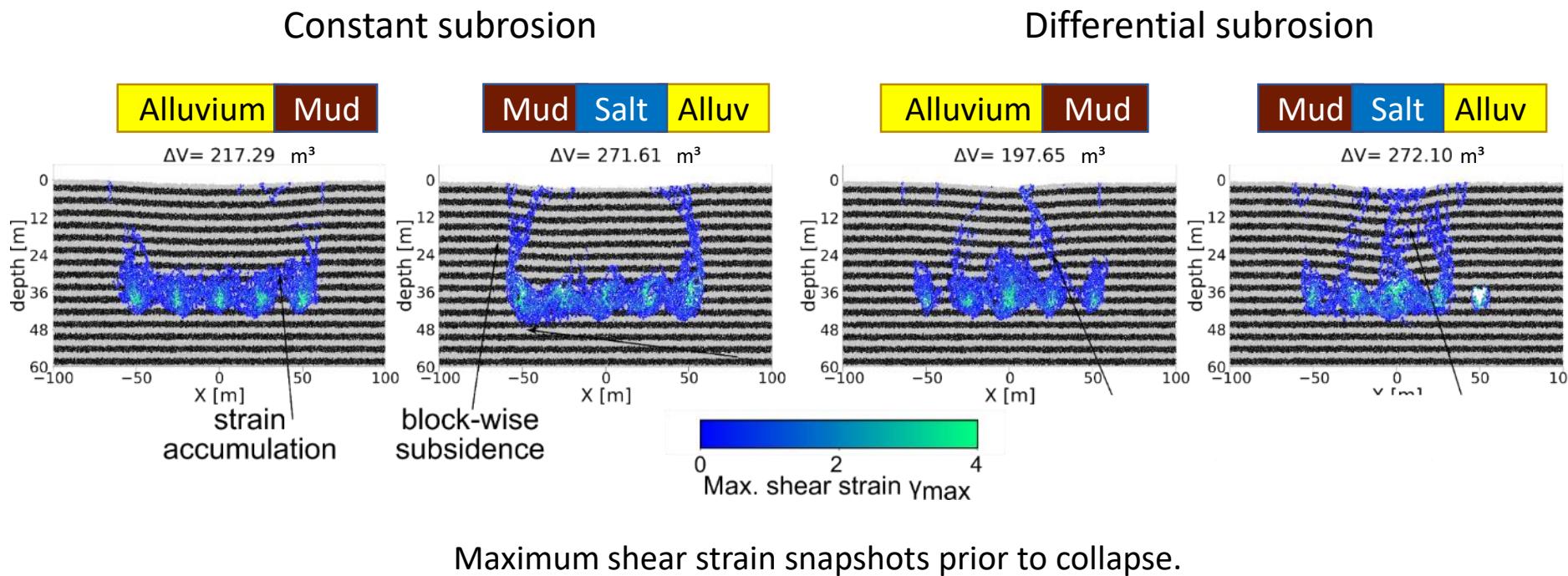
DEM models of individual sinkhole formation



DEM models of multiple sinkholes & large-scale depressions

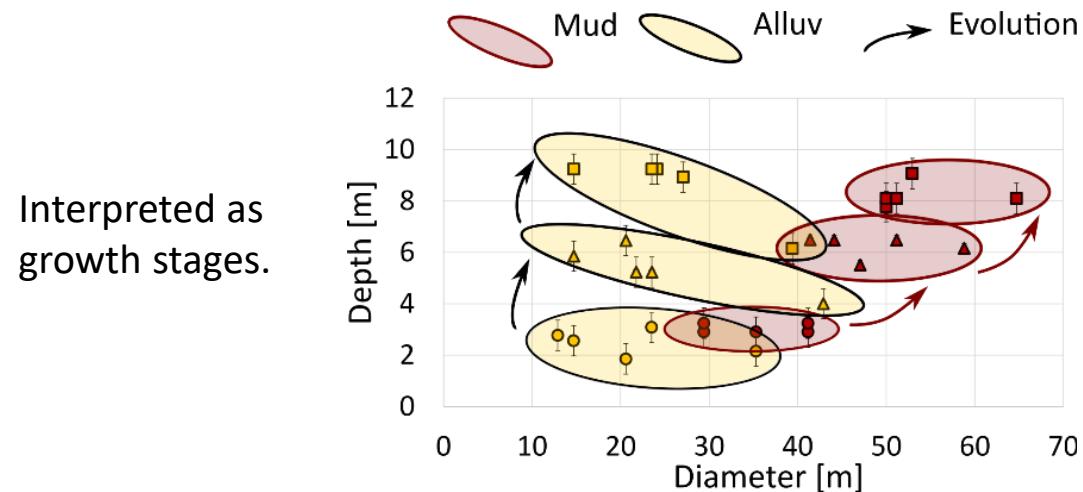
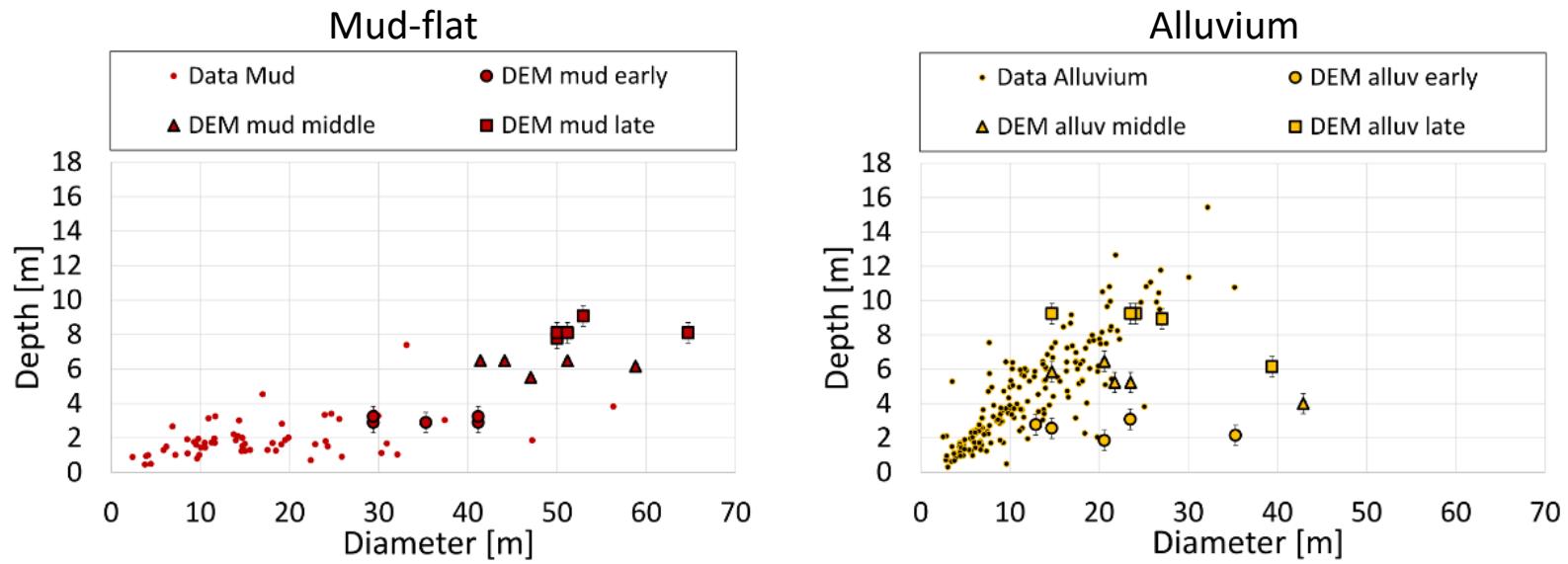


DEM models of multiple sinkholes & large-scale depressions



Comparison with morphological data

Individual sinkholes



Comparison with geophysical data

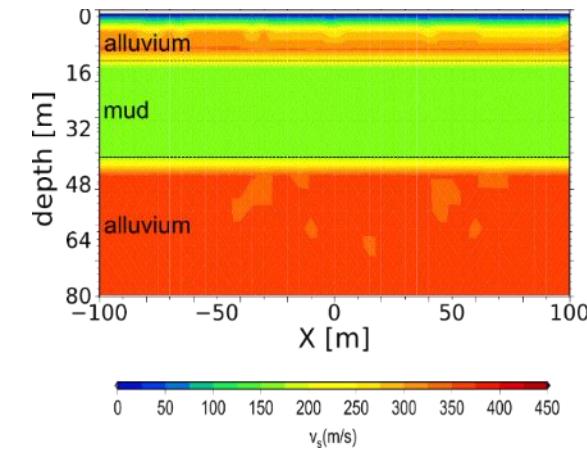
Field estimation by shear wave reflection seismics



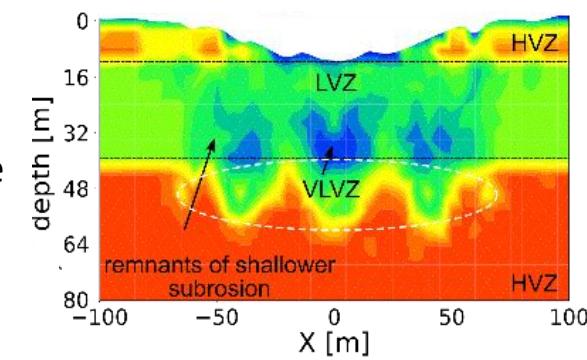
ELVIS landstreamer unit

Initial

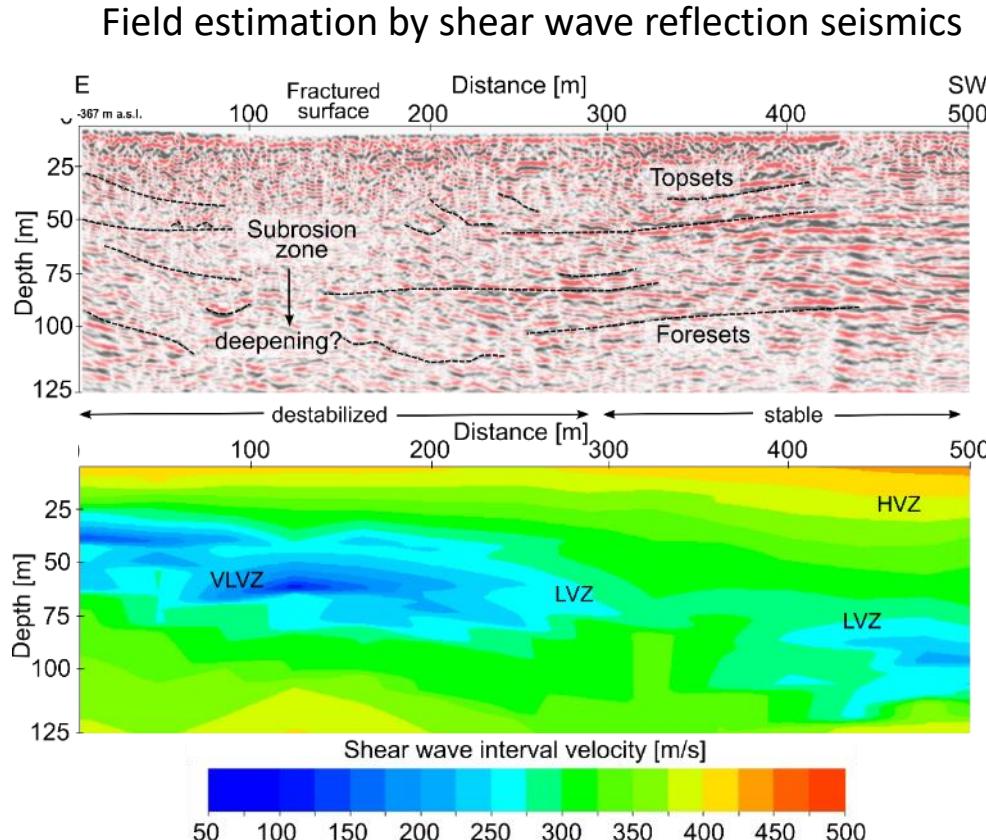
Simulated shear-wave velocities



Post-collapse

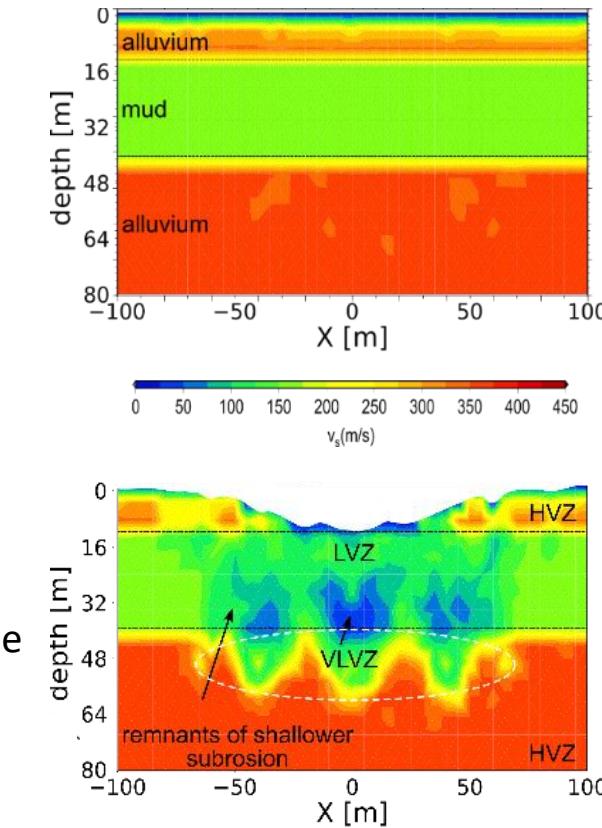


Comparison with geophysical data



Initial

Simulated shear-wave velocities



Post-collapse

Summary

1) Sinkhole morphologies & development in space & time:

- Clustered, elliptical sinkholes within large-scale depressions
- Deeper & narrower in alluvium, wider & shallower in mud/salt-flat

2) Mechanical development of sinkholes & clusters:

- Calibrated DEM approach for realistic sinkhole simulation
- Good agreement with morphometrics & structural features
- Formation is controlled by:
 - material strength in both overburden & cavity host material,
 - depth, geometry & relative speed of material removal
 - developed stress pattern in the subsurface
- The presence of a hard/soluble interlayer like salt under a mud layer is not necessary to reproduce the sinkhole morphology observed in the Gor Al-Hadita area

3) Geophysical parameters:

- Good agreement of seismic velocities reflecting the downward growth of the subrosion zone



Publications

DEM:

- Al-Halbouni, D., Holohan, E. P., Taheri, A., Schöpfer, M. P. J., Emam, S. and Dahm, T.: Geomechanical modelling of sinkhole development using Distinct Elements : Model verification for a single void space and application to the Dead Sea area, *Solid Earth*, 9, 1341–1373, doi:10.5194/se-2018-62, 2018.
- Al-Halbouni, D., Holohan, E. P., Taheri, A., Watson, R., Polom, U., Schöpfer, M. P. J., Emam, S. and Dahm, T.: Distinct Element geomechanical modelling of the formation of sinkhole cluster within large-scale karstic depressions, *Solid Earth Discuss.*, in review, doi:10.5194/se-2019-20, 2019.
- Al-Halbouni, D., Emam, S., Holoan, E. P., Taheri, A., Schöpfer, M. P. J., Dahm, T: PFC2D modelling of sinkhole cluster in karstic depressions. *Proceedings 5th International Itasca Symposium, Vienna, Austria -17-20 Feb* (2020).

Morphology:

- Al-Halbouni, D., Holohan, E. P., Saberi, L., Alrshdan, H., Sawarieh, A., Closson, D., Walter, T. R. and Dahm, T.: Sinkholes, subsidence and subrosion on the eastern shore of the Dead Sea as revealed by a close-range photogrammetric survey, *Geomorphology*, 285, 305–324, doi:10.1016/j.geomorph.2017.02.006, 2017.
- Watson, R. A. Holohan, E. P., Al-Halbouni, D., Saberi, L., Sawarieh, A., Closson, D., Alrshdan, H., Abou Karaki, N., Walter, T. R. and Dahm, T.: Sinkholes and uvalas in evaporite karst: spatio-temporal development with links to base-level fall on the eastern shore of the Dead Sea, *Solid Earth*, 10(4), 1451–1468, doi:10.5194/se-10-1451-2019.

Geophysics:

- Polom, U., Alrshdan, H., Al-Halbouni, D., Dahm, T., Sawarieh, A., Atallah, M. Y. and Krawczyk, C. M.: Shear wave reflection seismics yields subsurface dissolution and subrosion patterns: application to the Ghor Al-Haditha sinkhole site, Dead Sea, Jordan, *Solid Earth*, 9, 1079–1098, doi:10.5194/se-9-1079-2018, 2018.