

Testing Numerical Models of Subsalt Deformation through Field Observations: Case Studies from the Flinders Ranges, South Australia

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Motivation and Background

Drilling through salt sheets is dangerous because of the complex relationship between stress, fluid pressure and deformation in subsalt strata (Dusseault et al., 2004). This relationship evolves as deformation accumulates and the mechanical and hydrological properties of subsalt strata are progressively altered. Because even the best seismic data have difficulty resolving deformation beneath allochthonous salt sheets, researchers commonly turn to kinematical or numerical models of salt emplacement to predict the distribution and intensity of subsalt deformation. These models have not been rigorously tested against field and well data.

Nikolinakou et al. (2019) examined the evolution of a salt sheet and its adjacent minibasin and synkinematic sediments and predict a 1-2 km thick, ductile shear zone below salt (Figure 1a). Although “disturbed zones” up to a few hundred meters thick have been recognized beneath salt and are often attributed to halokinetic ductile shear, the origin and detailed characteristics of these zones are largely known from well logs (Saleh et al., 2013); physical studies of subsalt strata are rare. This study aims to fill that data gap by conducting detailed analyses of subsalt strata beneath two allochthonous salt sheets in the Flinders Ranges of South Australia. Additional studies of subsalt strata are presented elsewhere in this session by Lueck and Fischer (presentation EGU2020-21155).

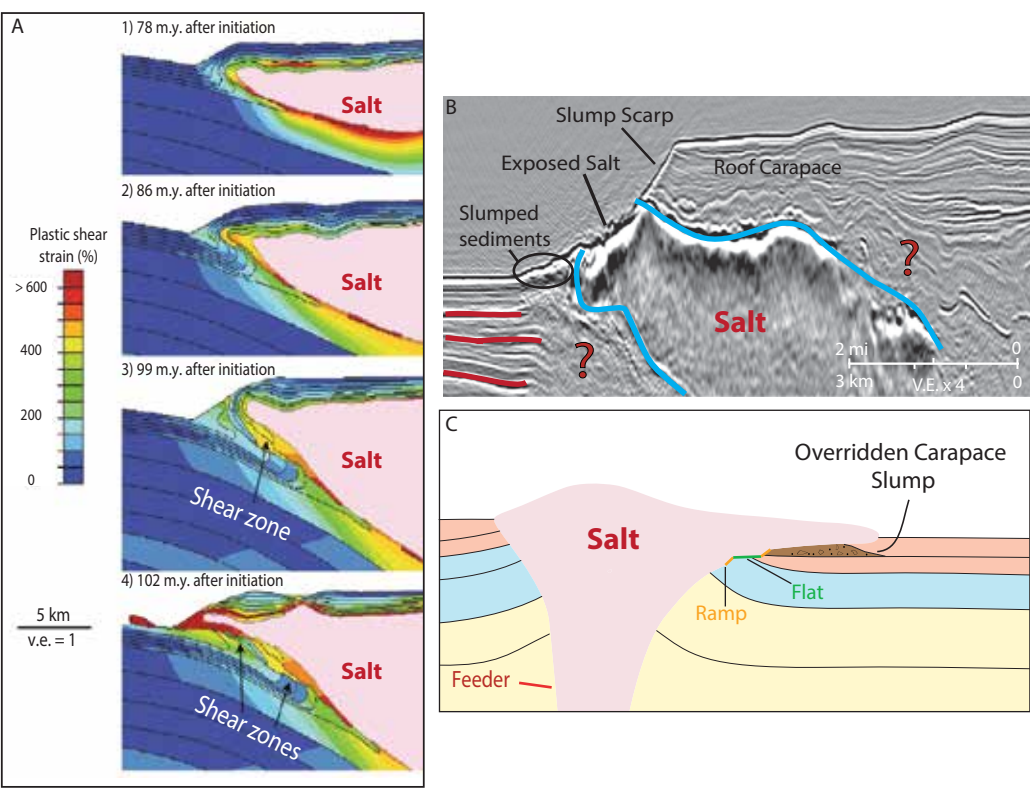


Figure 1. A) Geomechanical model by Nikolinakou et al. (2019) illustrating the evolution of plastic shear strain in roof sediments that are overturned in front of an advancing salt sheet. B) Seismic image modified from Hudec and Jackson (2006) illustrating roof carapace slumping. Note the poor resolution near the salt body. C) Schematic cross sectional diagram illustrating an allochthonous salt sheet overriding suprasalt carapace slumps.

Sheet-like allochthonous salt structures present in the Flinders Ranges have structural and stratal geometries analogous to those in the Gulf of Mexico (Rowan et al., 2019). Although these structures initiated in the Neoproterozoic, later regional-scale tilting and folding during the Delamerian Orogeny created an oblique, cross-sectional map view that allows for the detailed characterization of near-salt deformation at a scale of meters to hundreds of meters. Previous high-resolution mapping and mesoscopic structural analysis by Williams et al. (2018) established the pattern of deformation near a tertiary weld in the Willouran Ranges and provided a framework model in which to interpret the origin and timing of deformation near allochthonous salt. This study aims to apply, test and refine that framework using a methodology similar to that employed by Alsop et al. (2000) for diapirs in Nova Scotia.

In this study, we analyze deformation patterns present in the subsalt flats of two exposed allochthonous salt sheets (Figure 2). The thickness of the overlying salt sheet is >1 km at the Arkaroola field area and <1 km at the Arkaba field area. We use a combination of field mapping and 2-3 cm/pixel resolution drone imagery to conduct mesoscopic structural analysis that characterizes the deformation pattern in the strata adjacent to salt along transects at each field site.

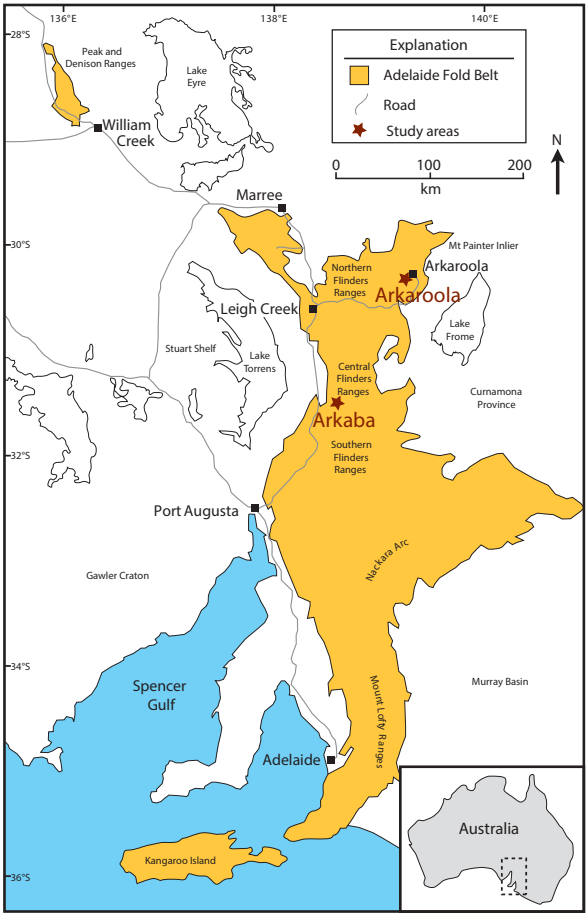
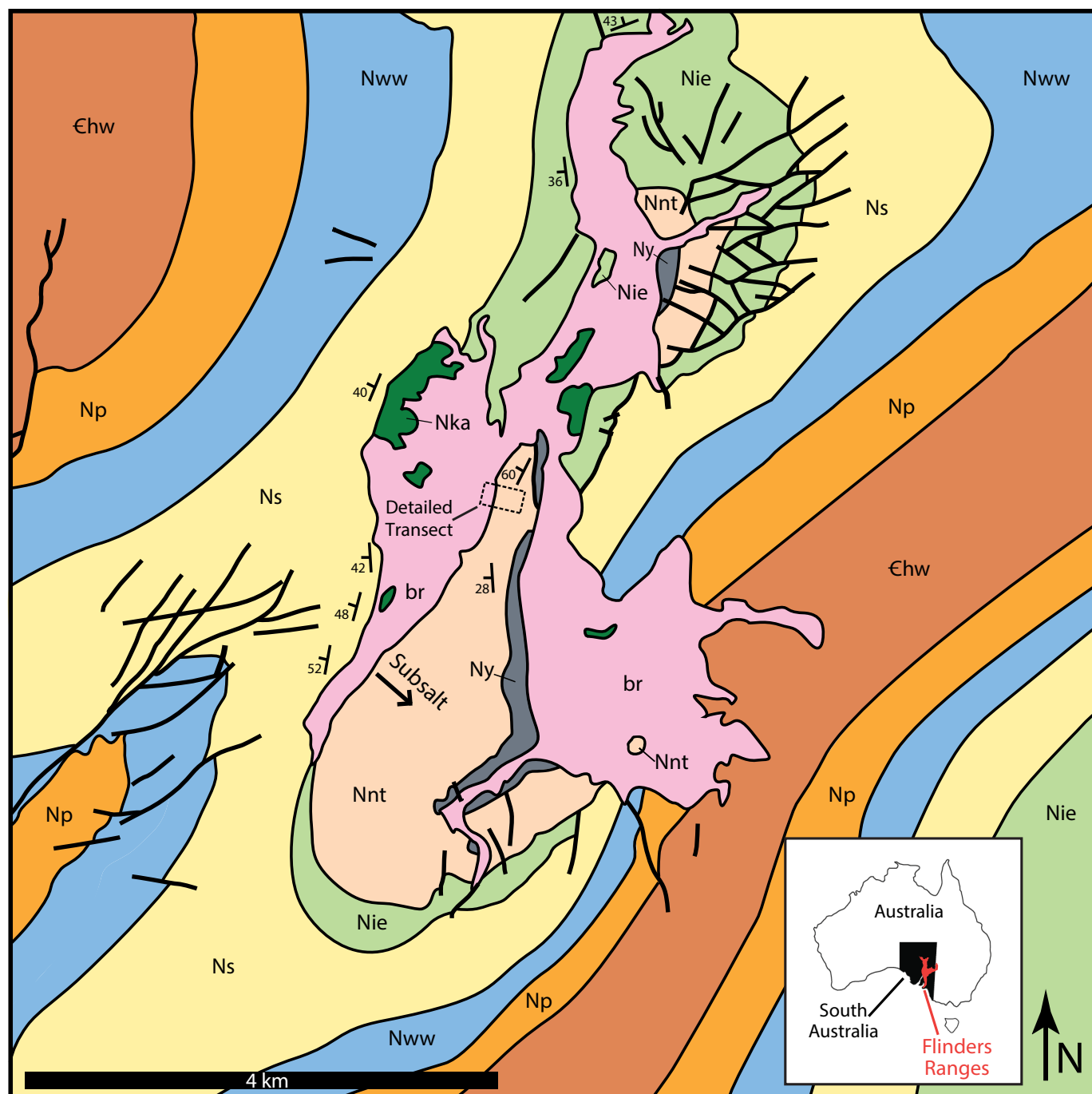


Figure 2. Generalized location map of the Adelaide Fold Belt modified from Hearon et al. (2015). Inset map shows the approximate location within Australia. Yellow shaded area represents the Adelaide Fold belt; red stars indicate the location of the two field areas. Arkaba is in the Central Flinders Ranges and Arkaroola is in the Northern Flinders Ranges.

Arkaba Field Area Map

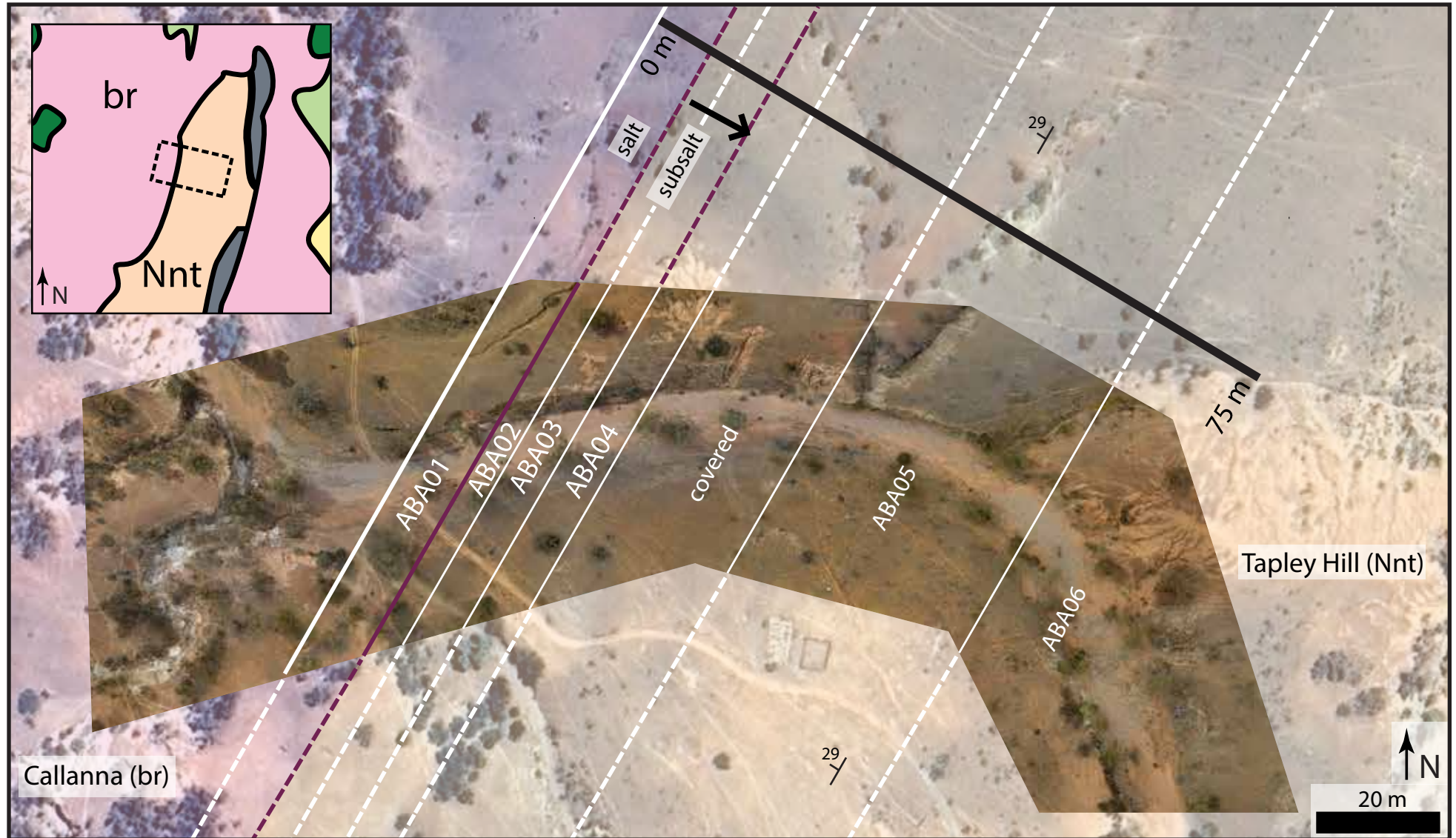


- Chw** Wilkawillina Limestone
Light to dark gray, massive, bedded lime mudstone, wackestone and isolated facies
- Np** Pound Subgroup
Quartzite; sandstone; red micaceous siltstone and sandstone; limestone and sandstone parasequences
- Nww** Wonoka Fm.
Shale, gray, calcareous; flaggy dolomite, limestone and silt
- Ns** Sandison Subgroup
Quartzite; siltstone and sandstone; dolomitic
- Nie** Enorama Shale
Laminated grey-green and minor red shale, silty shale and rare fine-grained sandstone
- Nnt** Tapley Hill Fm.
Siltstone, gray to black, dolomitic and pyritic grading upwards to calcareous, thinly laminated, locally cross-bedded; dolomite, gray, flaggy to massive
- Ny** Yudnamutana Supergroup
Blue-grey gritty siltstone and minor thin sandstone with pebble to boulder-sized glacial clasts
- Nka** Arkaba Hill Beds
Laminated stromatolitic dolomite and limestone
- Nc** Callanna Breccia (Salt)
Breccia, undifferentiated

Figure 3. Regional geologic map and stratigraphic column of the Arkaba field area based on the Hawker and Wilpena Quadrangles. The black outline represents the detailed field area in Figure 3.

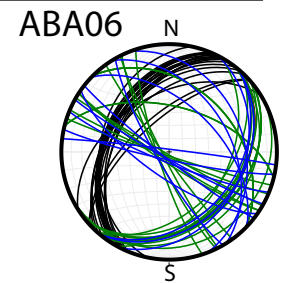
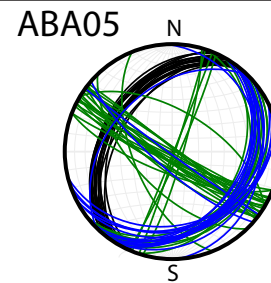
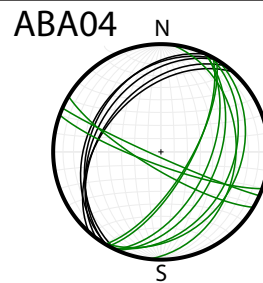
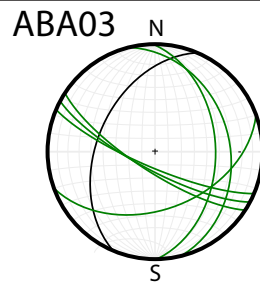
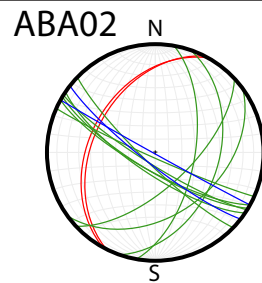
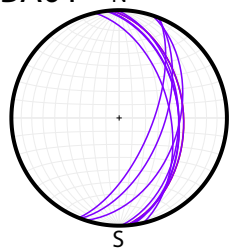
Arkaba Transect

Figure 4: Aerial photo of the Arkaba transect showing the extent of high resolution drone imagery. The transect line (heavy black) is oriented perpendicular to bedding. The transect starts in the Callanna and spans 75 stratigraphic meters into the subsalt flat across the Tapley Hill Formation. Local salt thickness above subsalt strata is >1 km.



Stereoplot Key

- Bedding
- Joints
- Veins
- Foliation



Near Salt Deformation at Arkaba

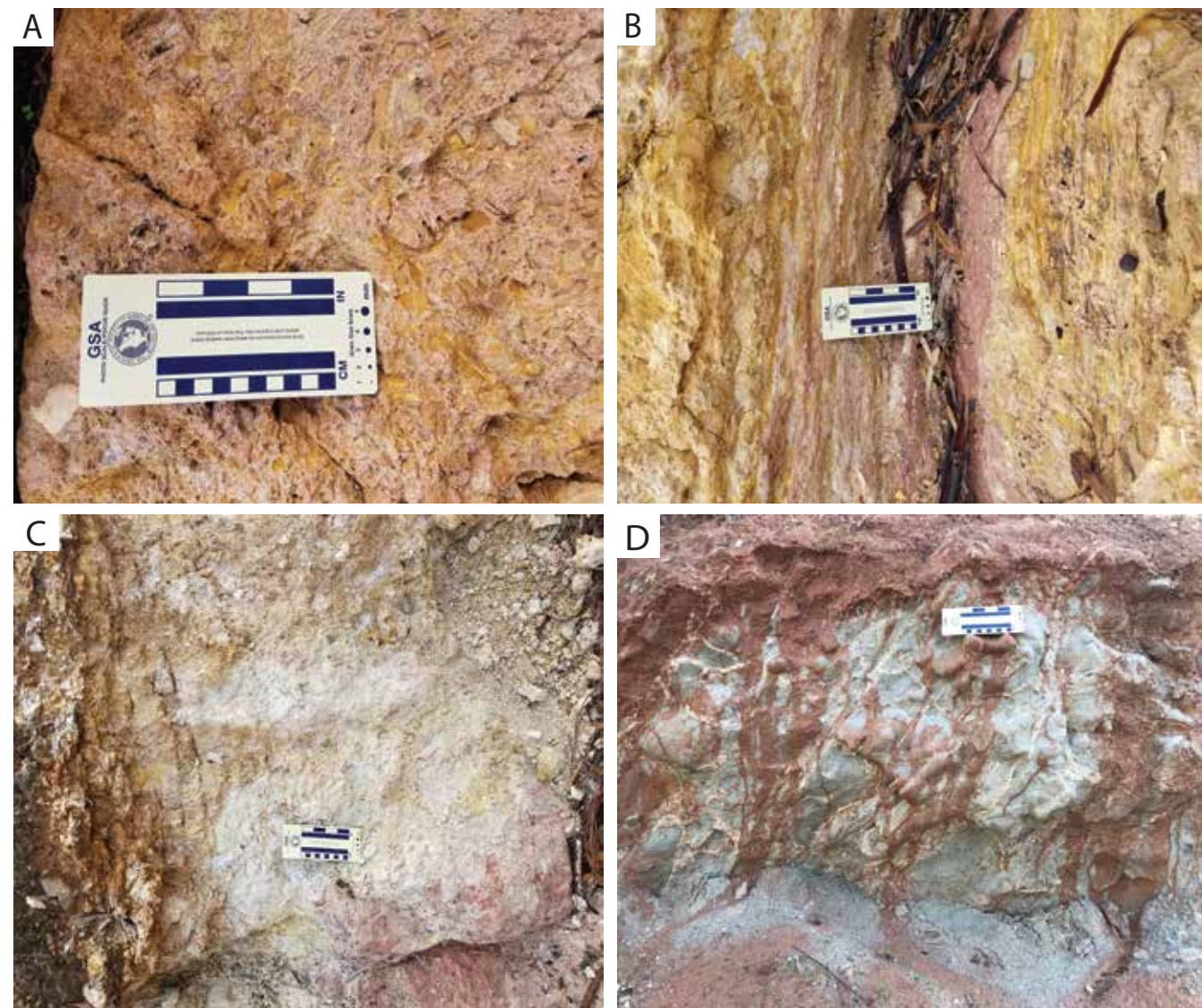
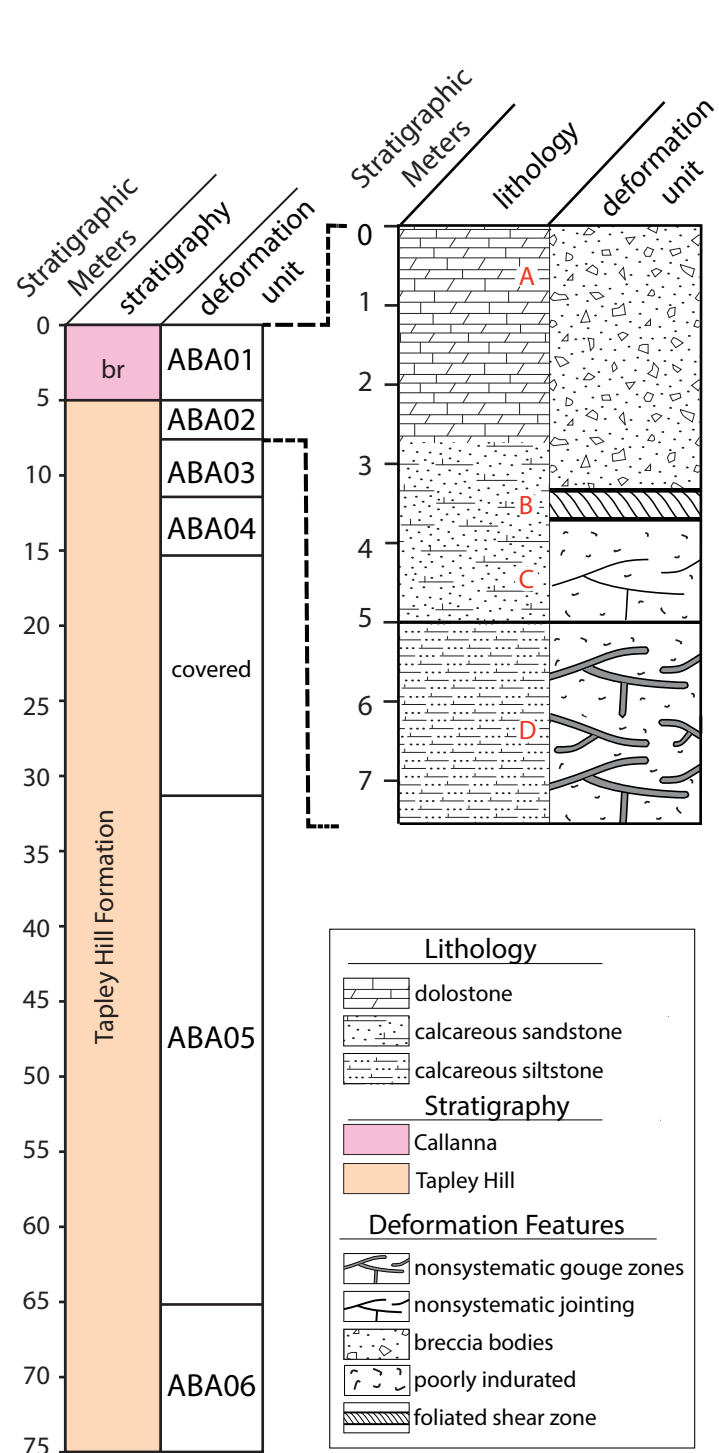


Figure 5. Lithostratigraphic and deformation details of stations ABA01 and ABA02 along the Arkaba transect. Station ABA01 is in the Callanna and station ABA02 is in the Tapley Hill Formation. A) Texture of Callanna dolomite breccia in ABA01. B) Strongly foliated zone in the Callanna. C) Poorly indurated calcareous sandstone at the base of ABA01. D) Thin, nonsystematic gouge zones characteristic of ABA02. Corresponding letters in column show position of photos.

Near Salt Deformation at Arkaba

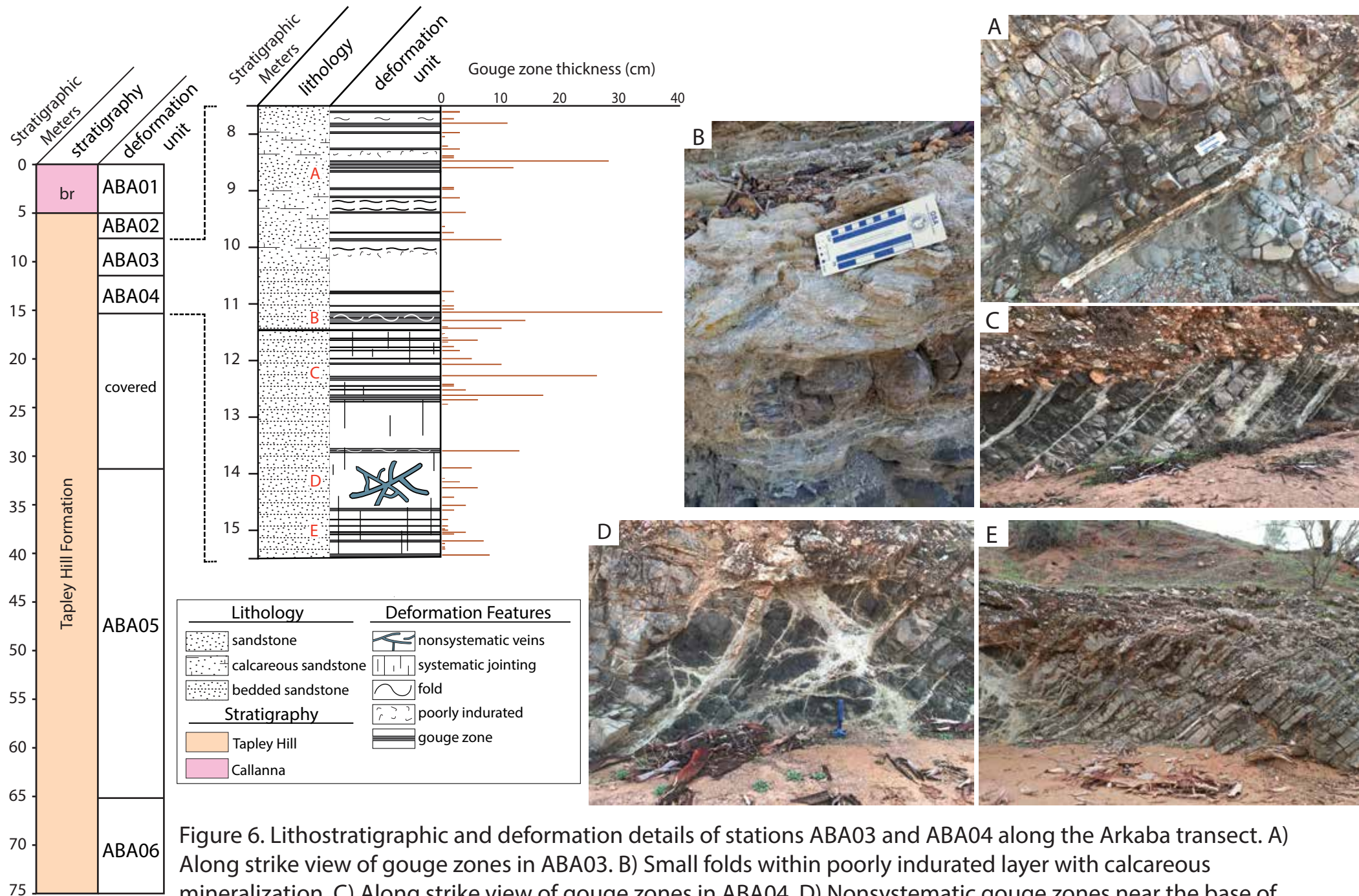


Figure 6. Lithostratigraphic and deformation details of stations ABA03 and ABA04 along the Arkaba transect. A) Along strike view of gouge zones in ABA03. B) Small folds within poorly indurated layer with calcareous mineralization. C) Along strike view of gouge zones in ABA04. D) Nonsystematic gouge zones near the base of ABA04. E) Fracture network at the base of ABA04. Corresponding letters in column show position of photos.

Near Salt Deformation at Arkaba

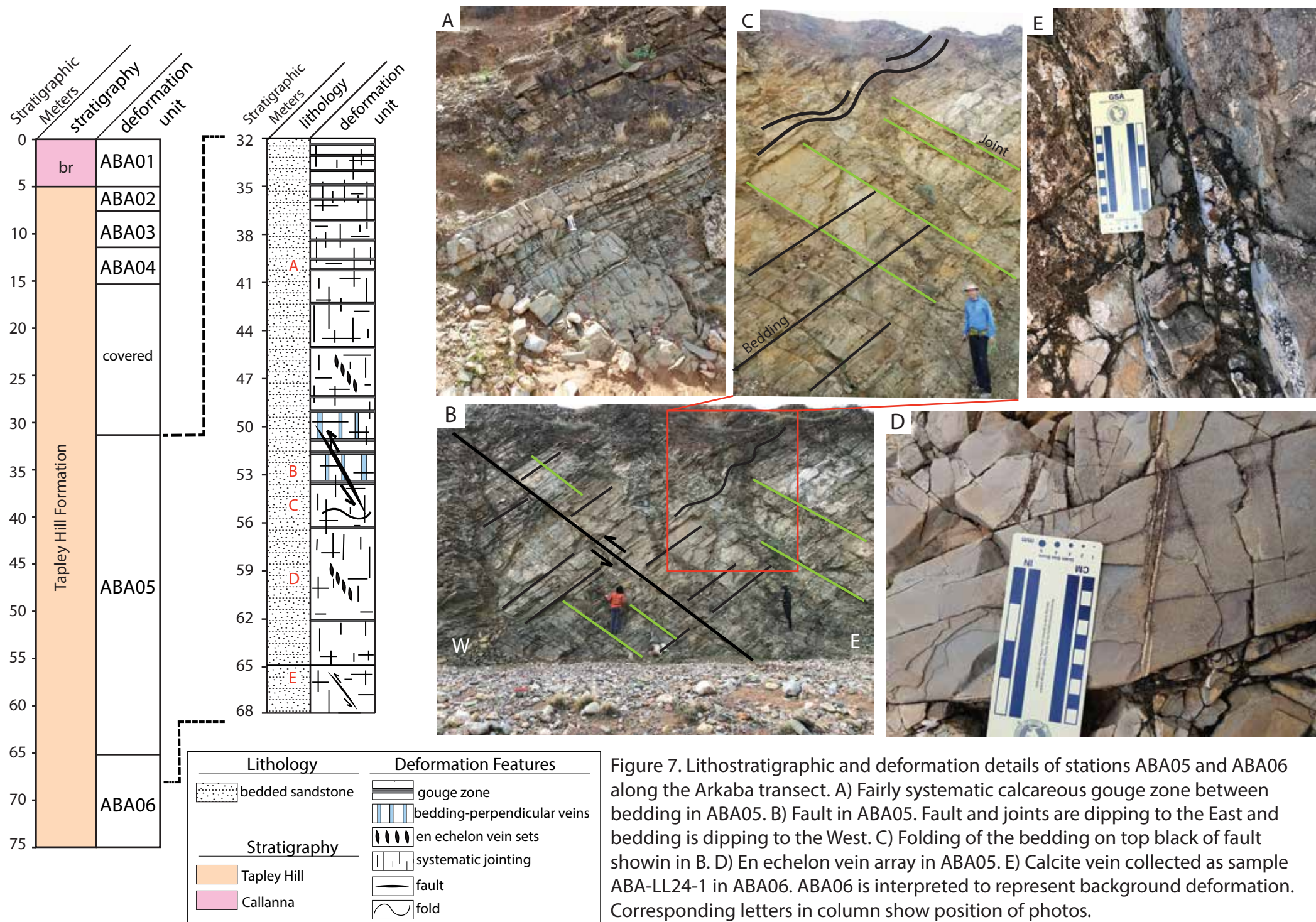
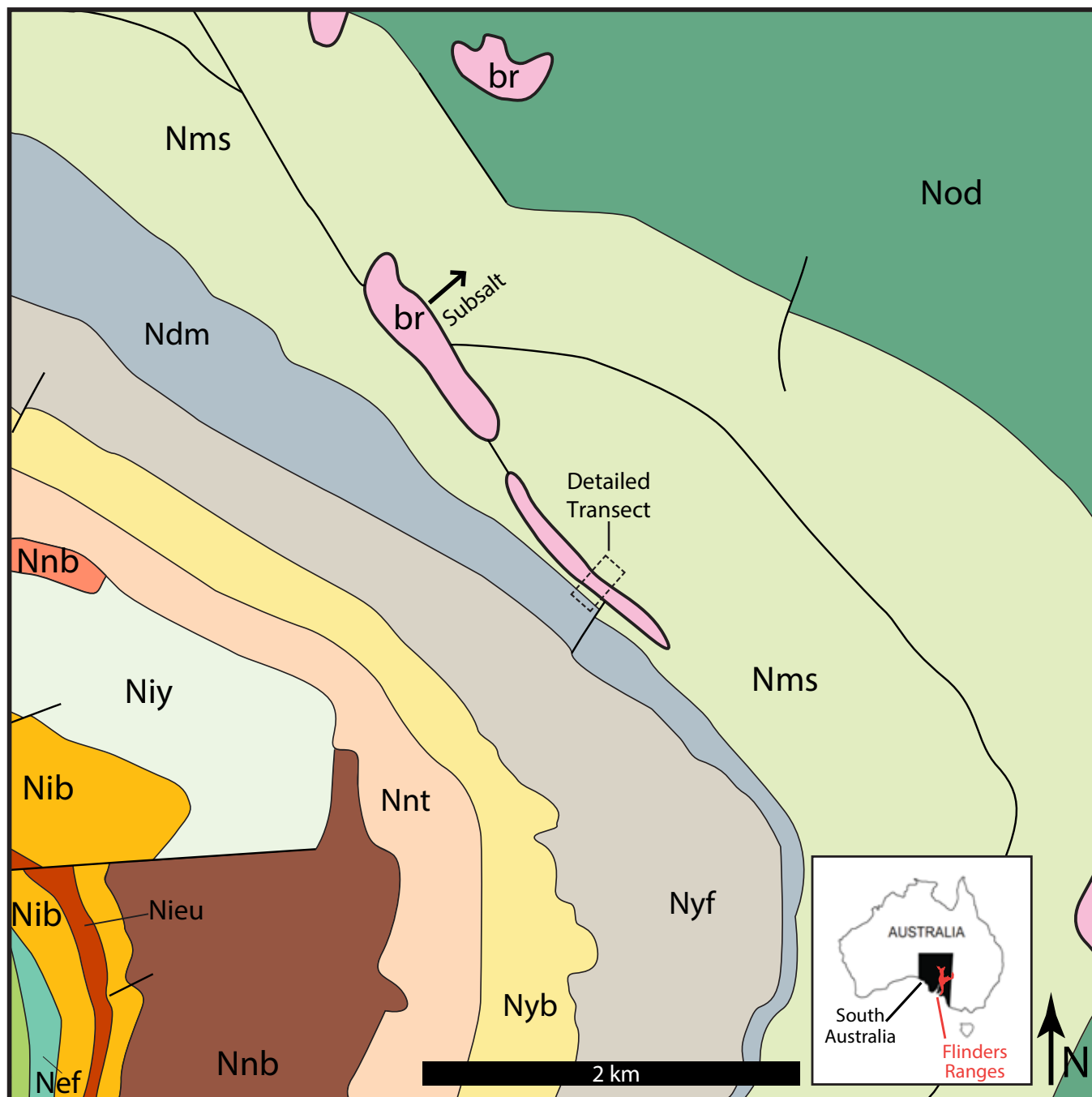


Figure 7. Lithostratigraphic and deformation details of stations ABA05 and ABA06 along the Arkaba transect. A) Fairly systematic calcareous gouge zone between bedding in ABA05. B) Fault in ABA05. Fault and joints are dipping to the East and bedding is dipping to the West. C) Folding of the bedding on top black of fault shown in B. D) En echelon vein array in ABA05. E) Calcite vein collected as sample ABA-LL24-1 in ABA06. ABA06 is interpreted to represent background deformation. Corresponding letters in column show position of photos.

Arkaroola Field Area Map



- Nee** Elatina Fm.
Sandstone, arkosic, medium-grained, red-brown, slumped
- Nef** Fortress Hill Fm.
Siltstone, gritty; dolomitic lenses and cobbles
- Nib** Amberoona Fm
Shale, green, finely laminated, silty, purple and gray silty shale
- Nieu** Wundowie limestone member
Limestone, gritty with stromatolite bioherms, oolitic, clay-pellets
- Niy** Yankaninna Fm
Siltstone, gray-green, thinly bedded, calcareous with lenses of dolomite
- Nnb** Balcanoona Fm
Dolomite, pale grey; limestone, dark grey, algal, oolitic
- Nnt** Tapley Hill Fm
Siltstone, gray to black, dolomitic and pyritic grading upwards to calcareous, thinly laminated, locally cross-bedded; dolomite, gray, flaggy to massive
- Nyb** Bolla Bollana Tillite
Tillite, massive, high boulder content, gritty, sub-gray wacke amtrix, minor quartzite
- Nyf** Fitton Fm
Conglomerate, arkose, pebbly; white, massive quartzite interbedded with silty shale
- Ndm** Myrtle Springs Fm
Siltstone, green; minor quartzite and dolomite
- Nms** Skillogalee Dolomite
Dolomite; marble with magnesite mud-pellet conglomerates
- Nod** Woodnamoka Phyllite
Phyllite; breccia; sandstone; arkose; argillaceous sandstone
- br** Callanna Breccia (Salt)
Breccia, undifferentiated

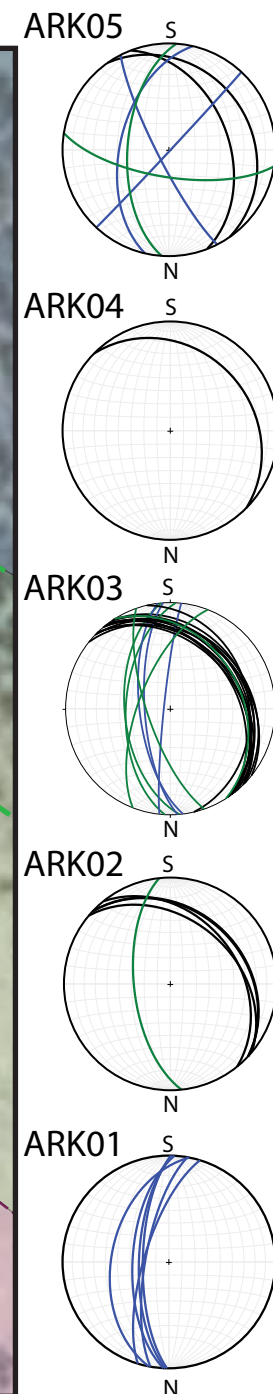
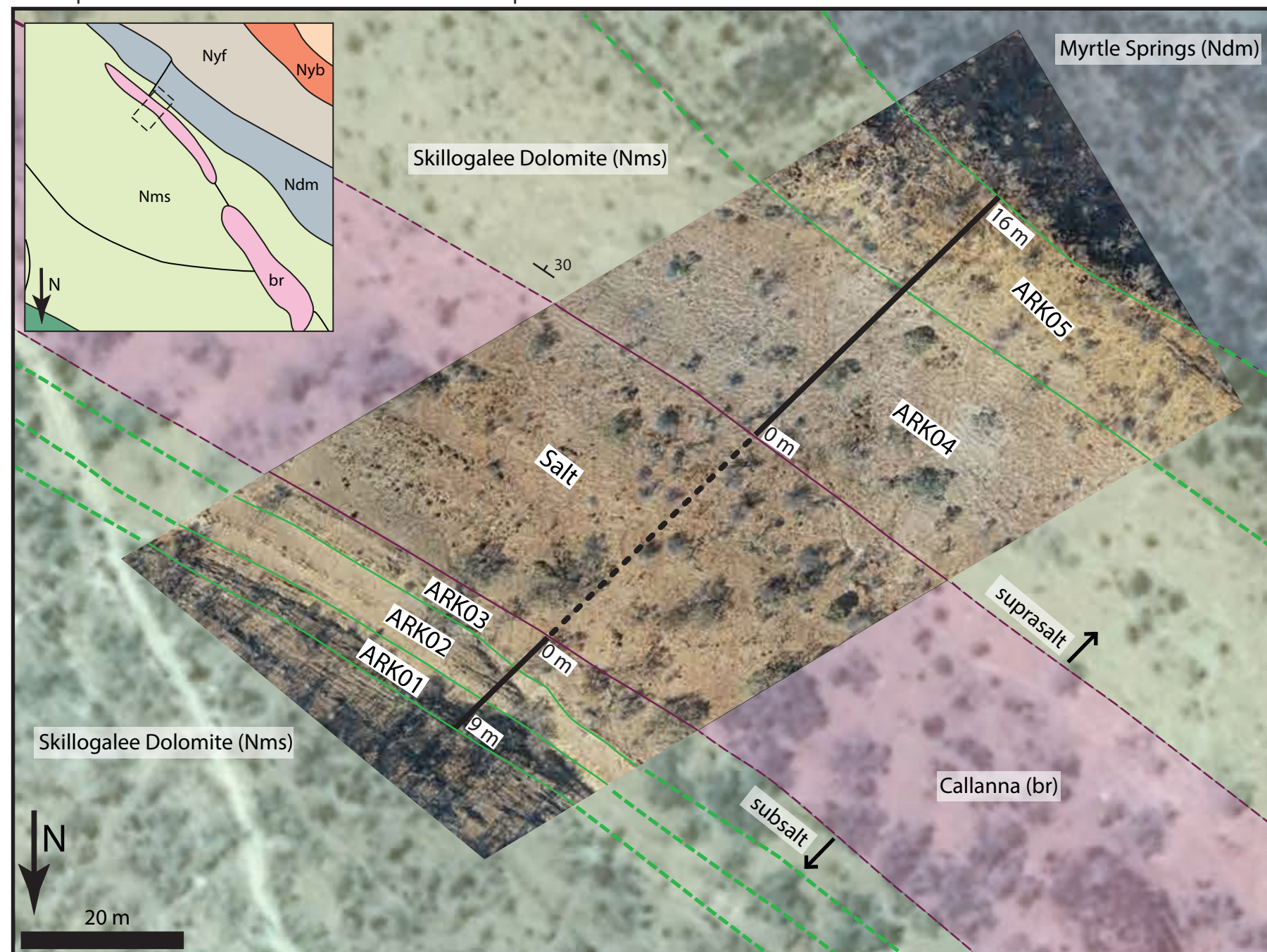
Figure 8. Regional geologic map and stratigraphic column of the Arkaba field area based on the Umberatana Quadrangle. The black outline represents the detailed field area in Figure 9.

Arkaroola Transect

Figure 9. Aerial photo of the Arkaroola transect showing the extent of high resolution drone imagery. The transect line (heavy black) is oriented perpendicular to bedding and starts at the subsalt- and suprasalt-sediment interface and moves away from salt. ABA01, ABA02, and ABA03 are in the subsalt flat and ABA04 and ABA05 are in the suprasalt. Transect distance spans 9 stratigraphic meters into the subsalt and 16 stratigraphic meters into the suprasalt across the Skillogalee Dolomite. Local salt thickness is <200 meters. Note: Stereoplots are shown with North down to match map orientation.

Stereoplot Key

Bedding	—
Joints	—
Veins	—



Near Salt Deformation at Arkaroola

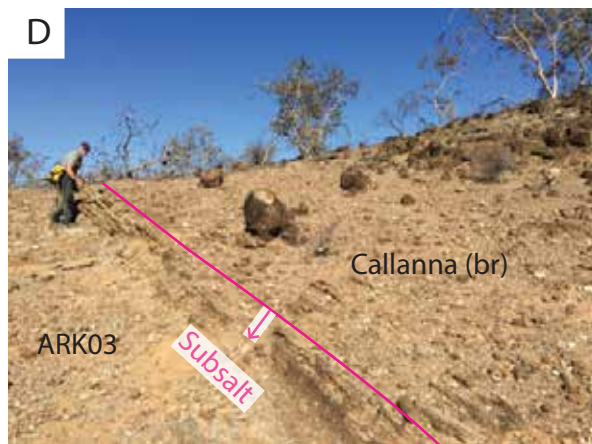
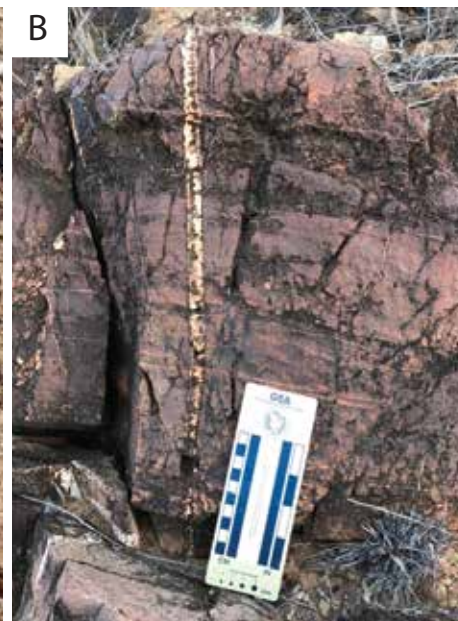
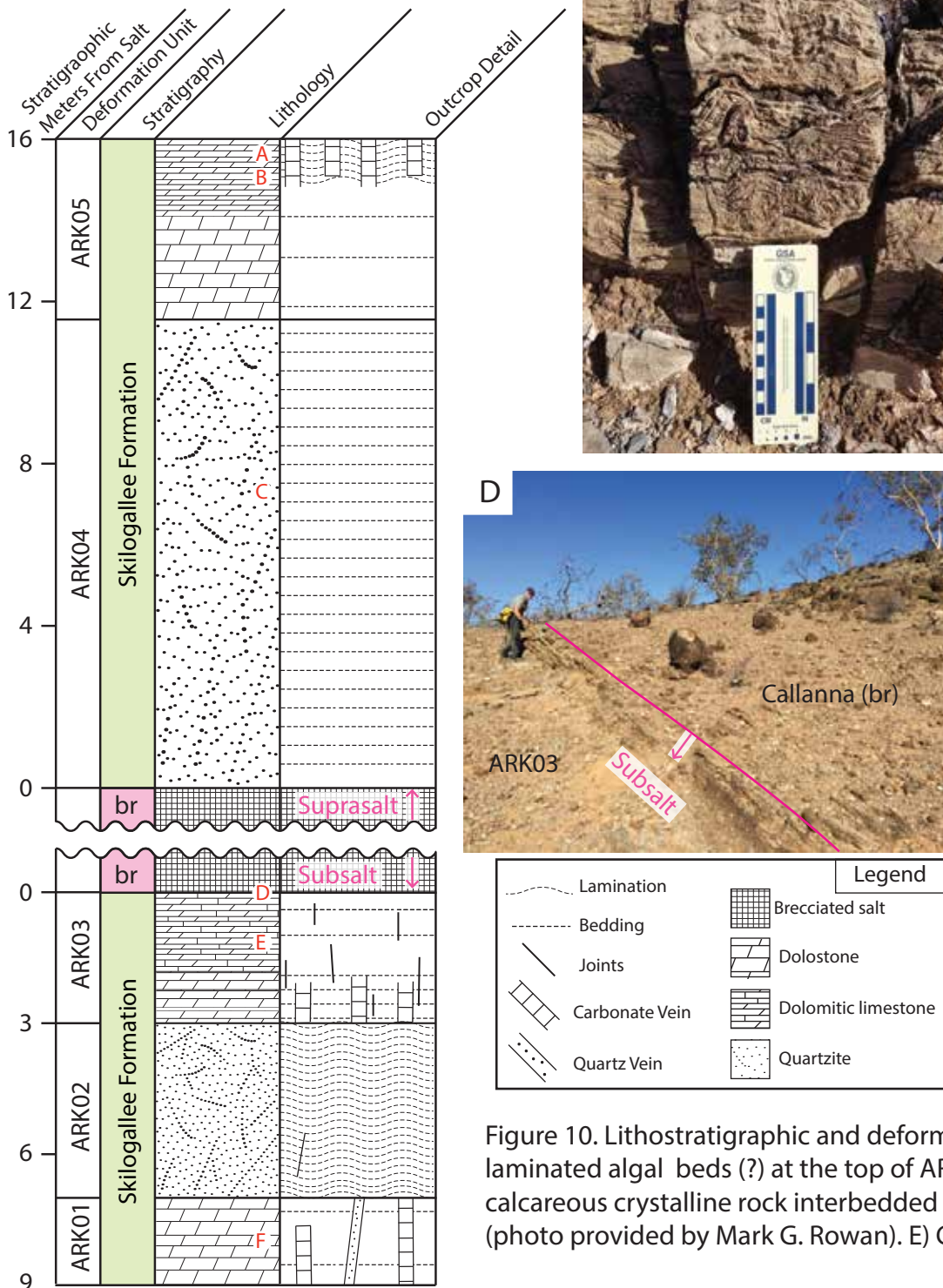


Figure 10. Lithostratigraphic and deformation details of stations located along the Arkaroola transect. A) Thinly laminated algal beds (?) at the top of ARK05. B) Quartz vein perpendicular to bedding in ARK05. C) Sample of calcareous crystalline rock interbedded with ARK04. D) Base-salt contact between the Skilgallee and Callanna (br) (photo provided by Mark G. Rowan). E) Close up of scapolite in ARK03. F) Dolomite and quartz vein in ARK01.

A landscape photograph showing a wide, flat, arid plain under a clear sky. A vibrant rainbow is visible in the distance, arching over the horizon. The foreground is covered in sparse, low-lying vegetation. The title 'Conclusions' is centered at the top of the image.

Conclusions

Deformation beneath the subsalt flats appears to correlate to the thickness of the overlying salt sheet.

- Where the preserved salt sheet thickness is < 200 m there is little to no mesoscopic deformation.

- Where the salt sheet is > 1 km thick, strata are brecciated near the salt-sediment interface, brittle fractures are abundant, and layer-parallel shear zones and mineralized fractures decrease in abundance downward in the stratigraphic section.

Our results suggest that existing numerical models overestimate the amount and stratigraphic extent of deformation beneath allochthonous salt sheets. Continued field study of near salt deformation will help to constrain future models and provide criteria to distinguish halokinetic and soft sediment deformation.

Prompts for Discussion

What are the most important controlling variables that influence near-salt deformation?

What are the most important field observations that we can use to discriminate between salt tectonic and other types of deformation (e.g., carapace slumping, synsedimentary folding, etc.)?

What does the term “rubble zone” mean to you?

References

Alsop, G.I., Brown, J.P., Davison, I., and Gibling, M.R., 2000, The geometry of drag zones adjacent to salt diapirs: *Journal of the Geological Society, London*, v. 157, p. 1019-1029.

Dusseault, M.B., Maury, V., Sanfilippo, F., and Santarelli, F.J., 2004, Drilling Around Salt: Risks, Stresses, and Uncertainties: Paper presented at the US Rock Mechanics and Geomechanics Symposium, Houston, TX, 5-9 June 2004 paper 04-647.

Hearon, T.E., Rowan, M.G., Giles, K.A., Kernen, R.A., Gannaway, C.E., Lawton, T.F., and Fiduk, J.C., 2015, Allochthonous salt initiation and advance in the northern Flinders and eastern Willouran ranges, South Australia: Using outcrops to test subsurface-based models from the northern Gulf of Mexico: *AAPG Bulletin*, v. 99, no. 2, p. 293-331.

Hudec, M.R. and Jackson, M.P.A., 2006, Advance of allochthonous salt sheets in passive margins and orogens: *AAPG Bulletin*, v. 90, no. 10, p. 1535-1564.

Nikolinakou, M.A., Heidari, M., Hudec, M.R., and Flemings, P.B., 2019, Stress and Deformation in Plastic Mudrocks Overturning in Front of Advancing Salt Sheets; Implications for System Kinematics and Drilling: *Rock Mechanics and Rock Engineering*, p. 1-14.

Saleh, S., Williams, K.E., and Rizvi, A., 2013, Rubble Zone Below Salt: Identification and Best Drilling Practices; *SPE 166115-MS*.

Williams, N.J., Fischer, M.P., and Canova, D.P., 2018, Structural evolution and deformation near a tertiary salt weld, Willouran Ranges, south Australia: *Marine and Petroleum Geology*, v. 102, p. 305-320.