Virtual field trip: the Eo-Variscan structures of the Eastern Moroccan Meseta (Debdou-Mekkam region)

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Introduction

During the amalgamation of the supercontinent Pangea (late Paleozoic, Variscan/Alleghanian orogeny) the northern margin of Gondwana was deformed due to its collision with Avalonia and Laurussia. In northern Morocco (Figure 0.1) this deformation was recorded by the Paleozoic (Cambrian-Carboniferous) metasedimentary sequence exposed in the Moroccan Mesetas.

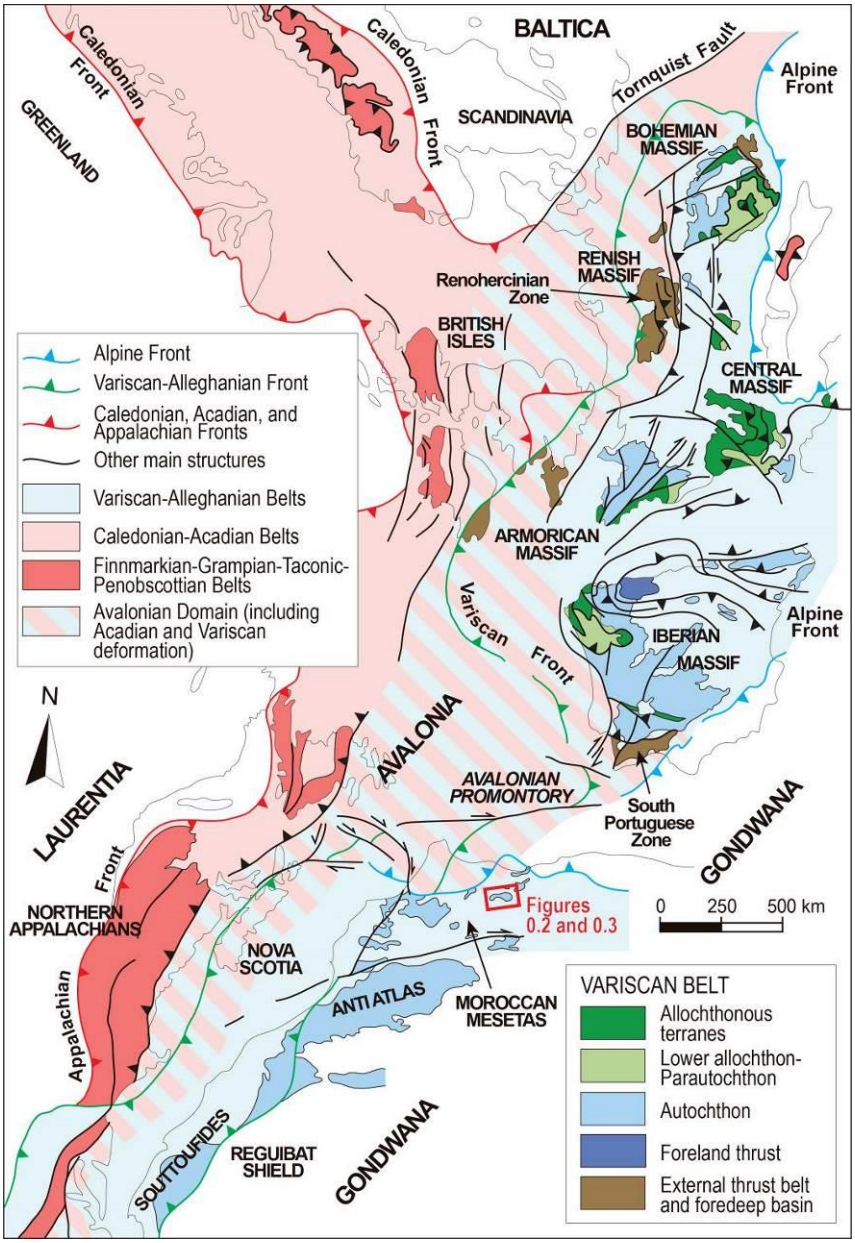

Figure 0.1: Regional reconstruction of the Variscan-Alleghanian, and Caledonian-Acadian belts (Late Paleozoic; modified from Martínez Catalán et al., 2002; Michard et al., 2010; Simancas et al., 2009).

This field trip is focused on the reconstruction of the earliest Variscan structures in the Debdou-Mekkam region (Eastern Moroccan Meseta; Figure 0.2). The area is characterized by the exposure of a thick monotonous sequence of phyllites, sandstones, and greywackes collectively called Debdou-Mekkam metasediments (DMMS). The maximum depositional age of the DMMS was determined to be Famennian-Tournaisian based on detrital zircon geochronology and their relationships with younger (Visean) rocks (Accotto et al., 2020). The DMMS are deformed by at least two deformational phases (Figure 0.3; Accotto et al., 2020; Hoepffner, 1989): an early Eo-Variscan event, which occurred during the Tournaisian-early Visean (here called D1 event), and the Variscan structures, formed during the late Carboniferous-Permian (here called the Dc event).

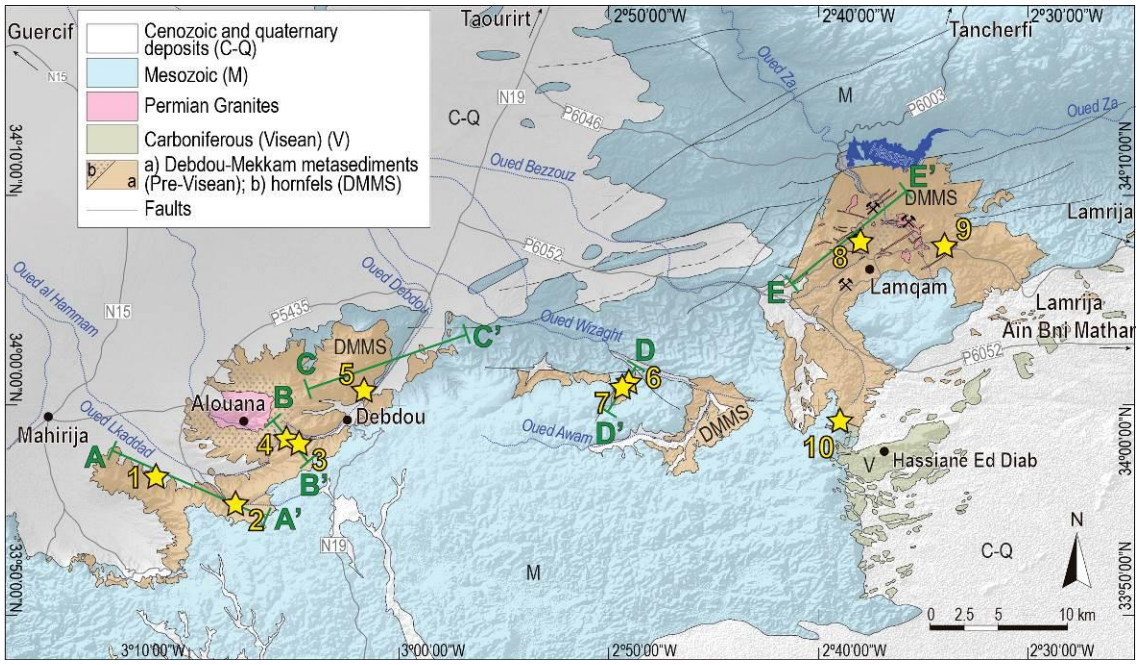

Figure 0.2: Debdou-Mekkam region (see location in Figure 0.1). The topographic base is the Digital Earth Model SRTM 1 Arc-second Global (https://earthexplorer.usgs.gov/), with a superimposed hillshade function to show altitude (after Accotto et al., 2020).

Based on provenance studies carried out on detrital zircon grains from DMMS samples, the area was interpreted by Accotto et al. (2020) as part of the northern Gondwanan margin (Figure 0.4a). The DMMS deposited in a forearc basin developed during the gradual approach of an Avalonian promontory to northern Gondwana during Late Devonian-Early Carboniferous time (Figure 0.4b). The collision of these two continents deformed the DMMS with the kilometric-scale, SE-verging folds observable in the Debdou-Mekkam region (Figure 0.4c).

In this field trip guide, ten sites are described from west to east, broadly following the regional cross-section proposed by Accotto et al. (2020) (Figure 0.3). Most of the sites (Figure 0.2 and 0.3) can be reached with a 4x4 vehicle along dirt roads, although road conditions may be poor. It is not recommended to drive on these roads at night or during adverse weather conditions. More details about how to reach the most problematic points are collected in the appendix of this guide.

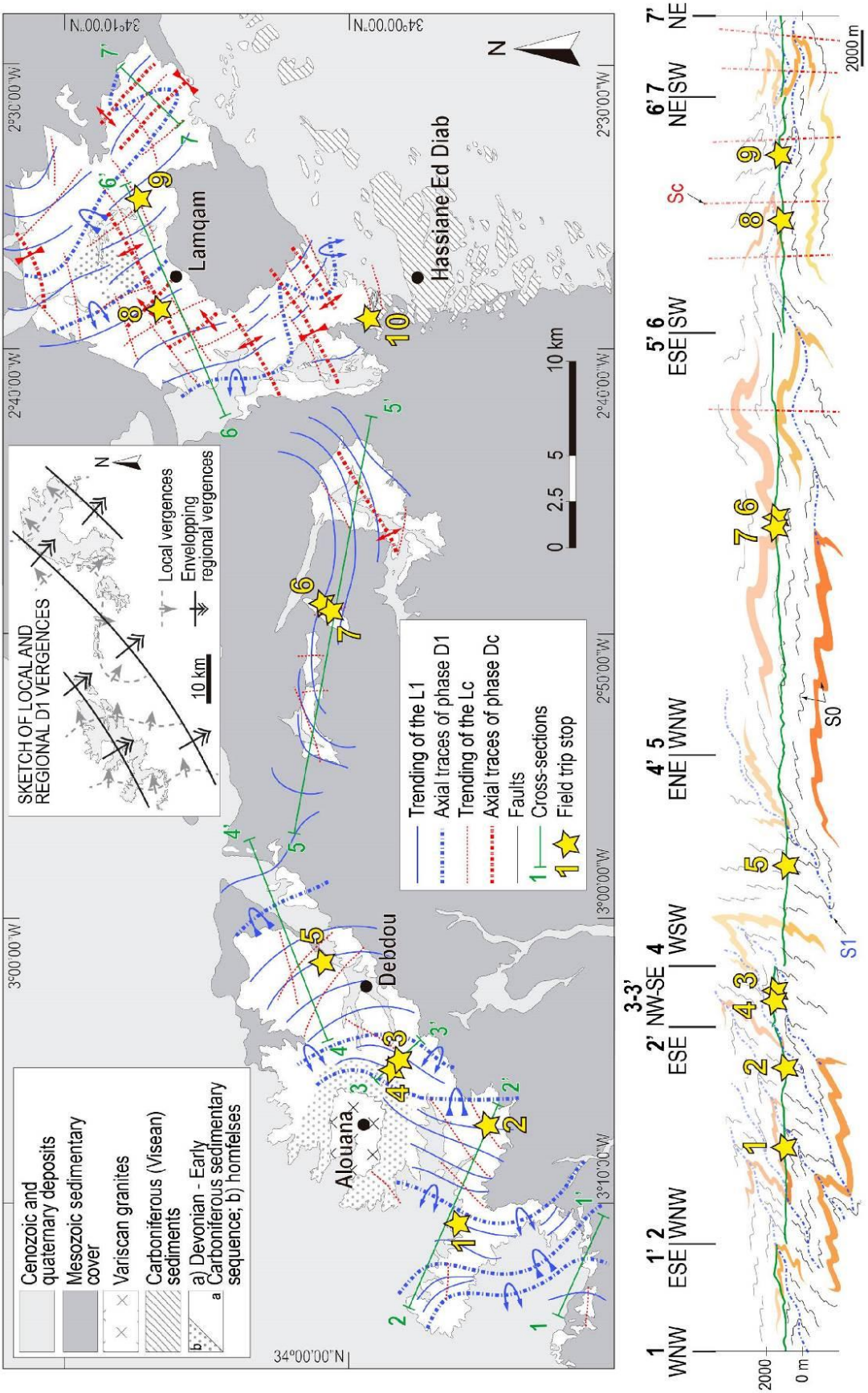

Figure 0.3: Schematic map and cross sections of the Debdou-Mekkam region. Colors of the different structural elements in the cross sections correspond to those in the map. Inset: sketch of the local and inferred regional vergences of the D1 structures (after Accotto et al., 2020).

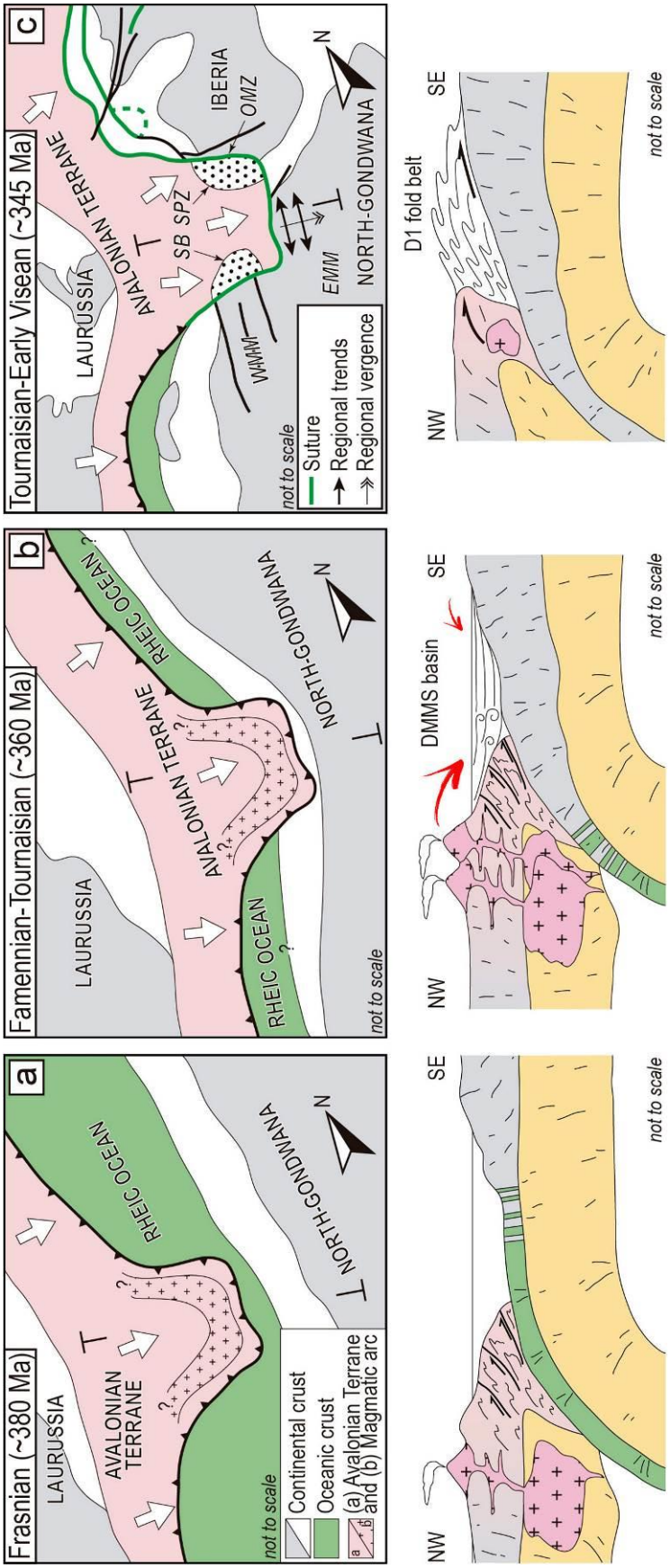

Figure 0.4: Large-scale schematic reconstruction of the tectonic evolution of the studied region from Frasnian (a) to Early Visean (c). SPZ: South Portuguese Zone; OMZ: Ossa-Morena Zone (Accotto et al., 2020).

1. Normal limb of Oued Lkaddad

(WGS84 UTM coordinates: 30S, 482150mE, 3755676mN)

The outcrop is located in a watershed after a small abandoned quarry. The predominant lithology is slate, with subordinate cm- to dm-thick beds of sandstone. Locally, some cross-cut laminations are preserved in the sandy layers (Figure 1a) showing normal polarity.

The beds are folded by parasitic folds showing SE vergence (Figure 1b). In the slaty levels a pervasive axial-planar foliation is developed (S1).

This area corresponds to the normal limb of a pluri-km-scale inclined anticline with SE vergence (Figure 1c).

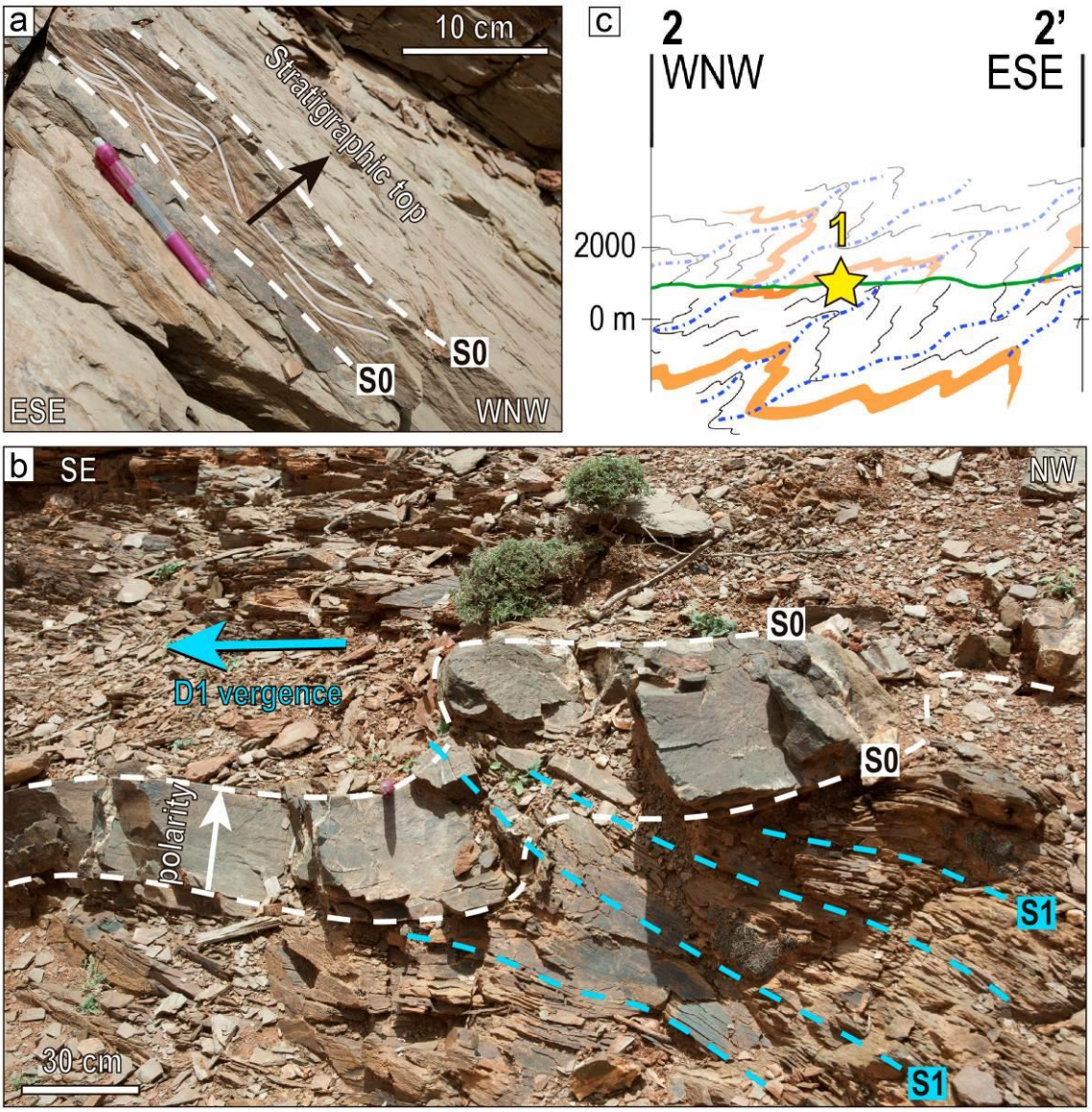

Figure 1: (a) Sandy level of the DMMS with truncated laminations indicating normal stratigraphic polarity; (b) parasitic fold in a sandy layer of the DMMS showing the local vergence and the development of axial-planar cleavage in the slaty beds; (c) cross section showing the location of the stop within the regional-scale structural reconstruction (see also Figure 0.3; after Accotto et al., 2020).

2. Reverse limb of Oued Lkaddad

(WGS84 UTM coordinates: 30S, 488310mE, 3753312mN)

The valley of the Oued Lkaddad is characterized by several outcrops of DMMS, accessible along a dirt road. Most of these outcrops show reversed stratigraphic polarity, mainly defined by downward decreasing grading (Figure 2a) of the sandy beds. The geometric relationships between the bedding (S0) and the cleavage (S1) show local west-vergence.

Overall, the valley is a reverse limb of a km-scale inclined E-vergent anticline. Plurimetric-size parasitic folds are very well exposed at the point where the road crosses the river. Their geometries suggest the presence of a syncline hinge zone (Figure 2b and c).

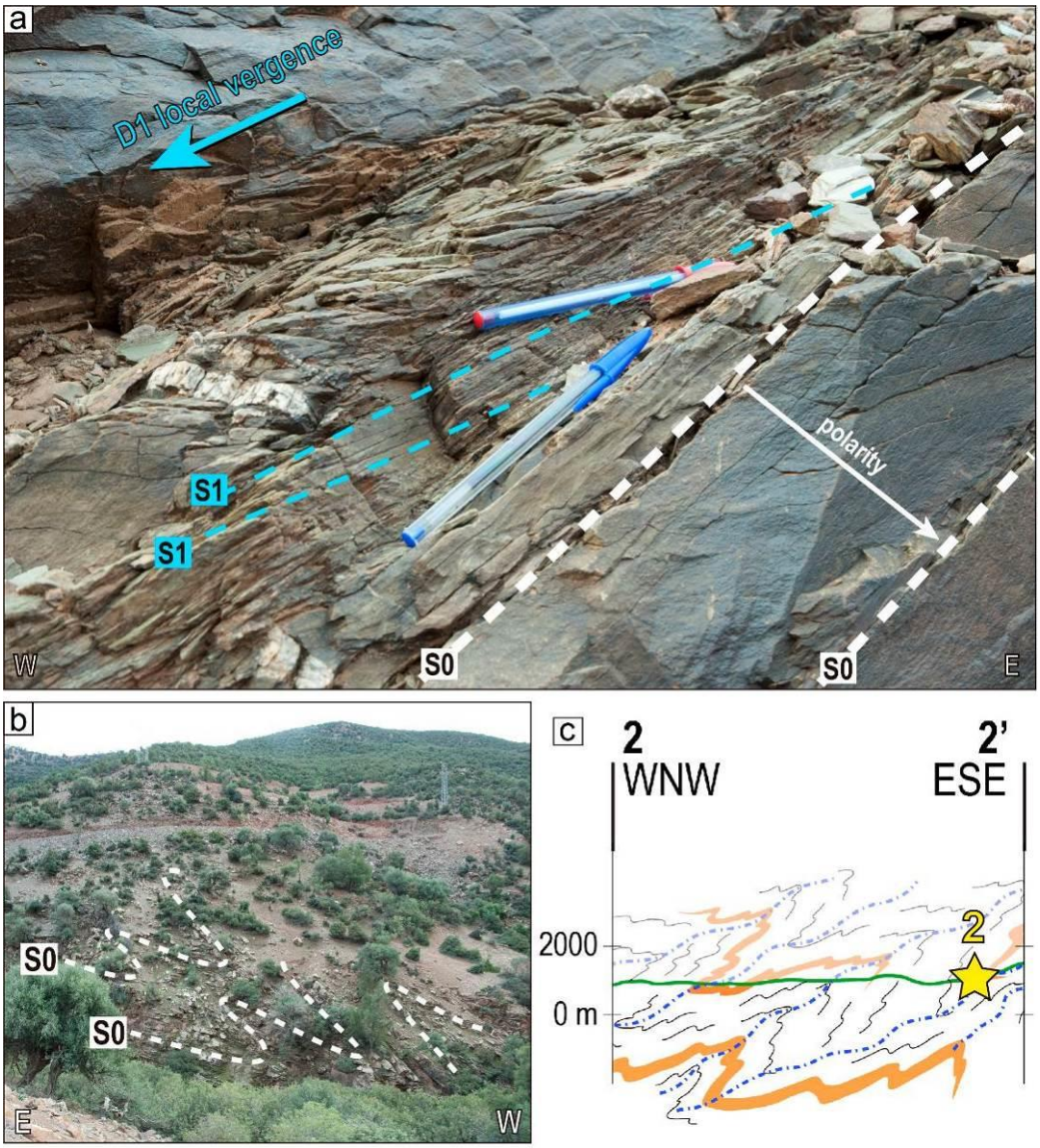

Figure 2: (a) structural relationships between overturned bedding (S0) and cleavage (S1) showing local W vergence and suggesting the presence of an overturned fold limb; (b) second-order parasitic folds showing a syncline hinge-zone; (c) cross section showing the location of the stop within the regional-scale structural reconstruction (see also Figure 0.3; after Accotto et al., 2020).

3. Anticlinal hinge of Debdou

(WGS84 UTM coordinates: 30S, 492834mE, 3757326mN)

The road that runs along the watershed on top of the Al Kbila area (Sidi Mimoun) cross-cuts a SE-plunging hinge zone as a result of the Dc folding phase. The area is characterized by sandy beds (Figure 3). The beds are folded in a series of metre-scale parasitic folds showing mainly M-geometries, and rapidly changing polarity of the beds (Figure 3). Where the geometry of the parasitic fold is asymmetric, it shows E-vergence, but the hinge zone appears to plunge towards the SE, suggesting that the later deformational event Dc has refolded the pre-existing structures in this area (Figure 3).

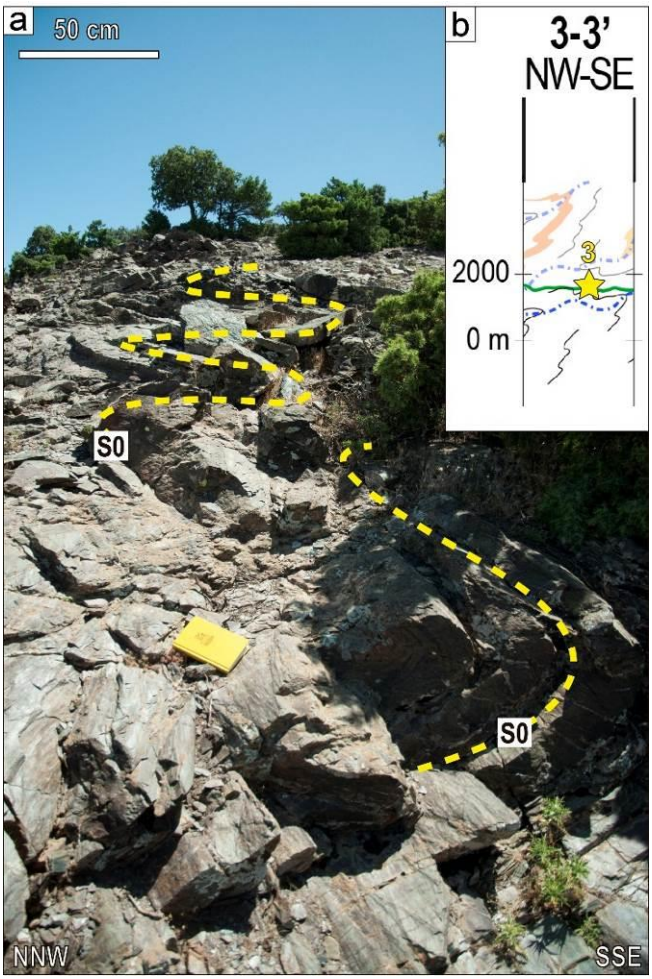

Figure 3: (a) M-geometries of parasitic folds in a hinge zone; (b) cross section showing the location of the stop within the regional-scale structural reconstruction (see also Figure 0.3; after Accotto et al., 2020).

4. Crenulation and thermal aureole between Debdou and Alouana

(WGS84 UTM coordinates: 30S, 491946mE, 3758626mN)

Continuing on the same road towards the NW, the structures related to the D1 deformational event are obliterated by a gradually increasing intense crenulation cleavage (Figure 4a) that has locally produced tectonic banding.

Furthermore, the rocks gradually change their aspect towards the NW (Figure 4b), close to the Alouana granitoid (not exposed in this area). Crystals of andalusite appear in the slates and sandstones and increase northwestward, obliterating the original texture of the DMMS (Figure 4c) and both the D1 and Dc structures.

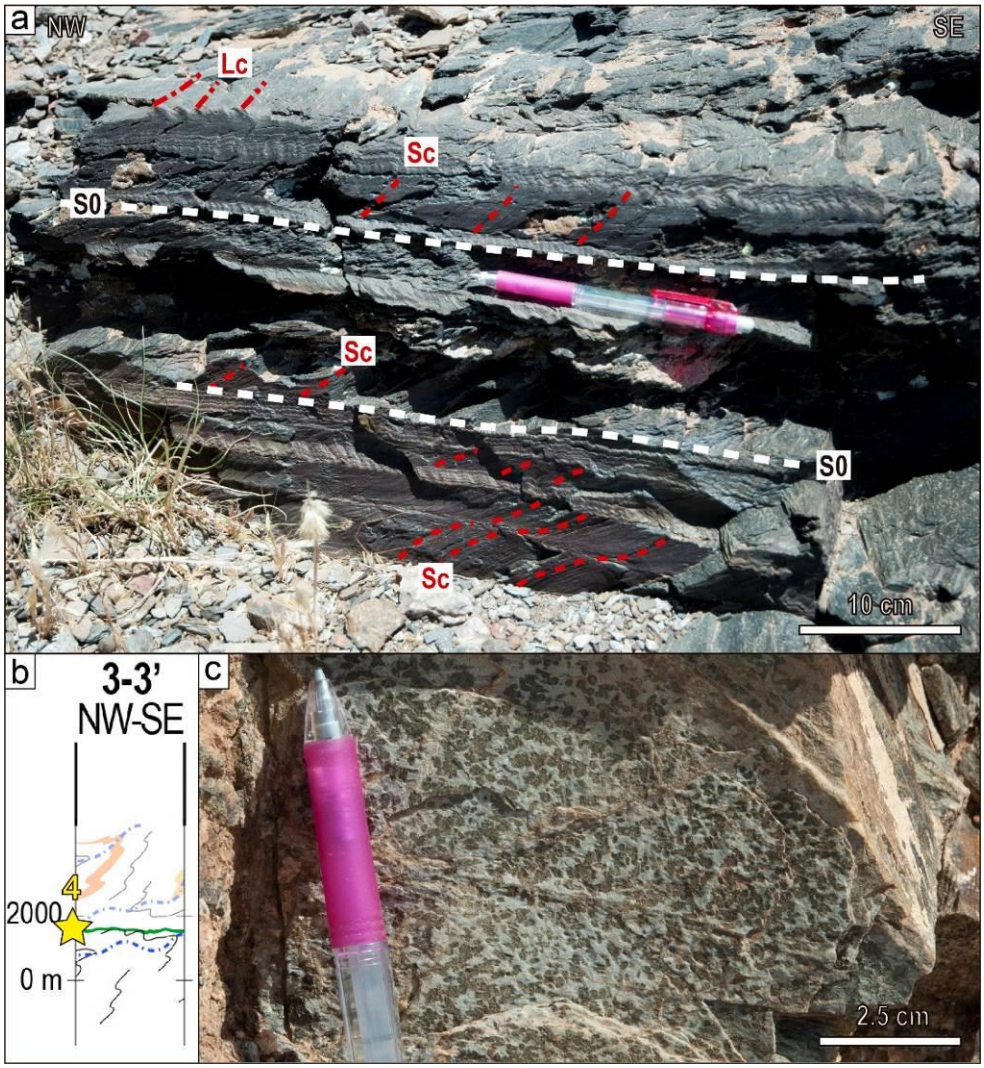

Figure 4: (a) Intense crenulation cleavage (Sc) developed in the slaty beds; (b) cross section showing the location of the stop within the regional-scale structural reconstruction (see also Figure 0.3; after Accotto et al., 2020); (c) DMMS affected by contact metamorphism.

5. Reverse limb of Debdou

(WGS84 UTM coordinates: 30S, 497300mE, 3762719mN)

In the Debdou valley (Figure 5a) several outcrops of DMMS show reversed stratigraphic polarity, but the structural relationships between S0 and S1 are commonly obliterated by intense crenulation. At site 5, there is an outcrop that preserves both S0 and S1 (Figure 5b). The stratigraphic polarity is reversed, expressed by the downward fining of the sandy beds. The geometric relationships between S0 and S1 show local SW vergence. Therefore, in the Debdou valley (at least between the village and site 5) the overturned limb of a km-scale inclined NE-vergent anticline (see cross-section in Figure 5a) is exposed.

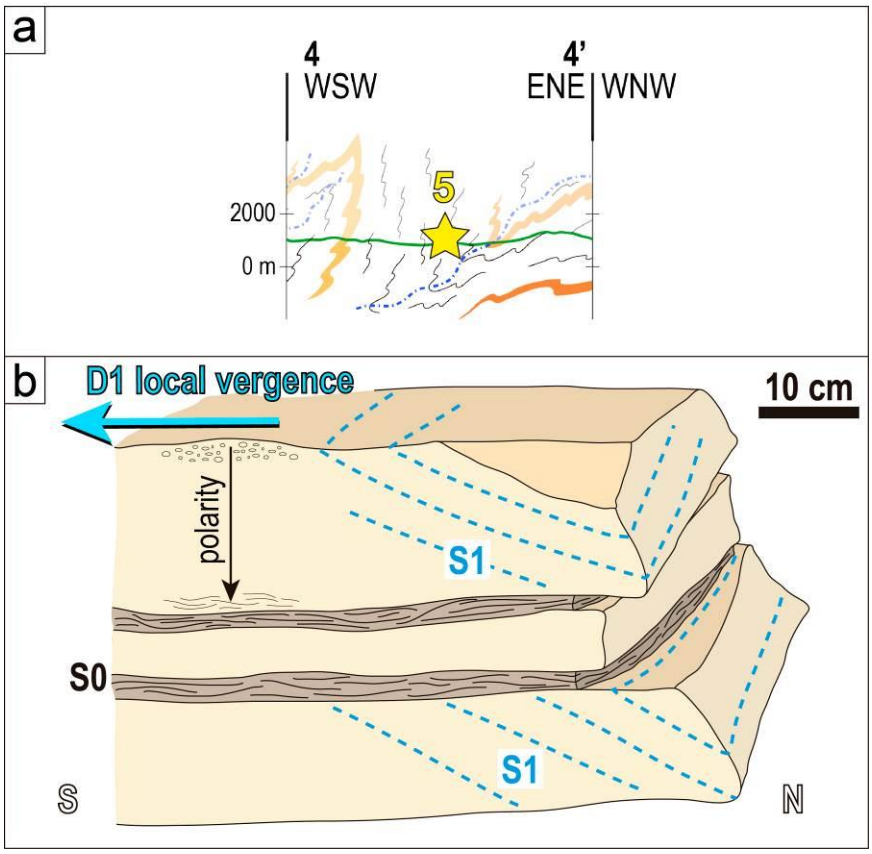

Figure 5: (a) cross section showing the location of the stop within the regional-scale structural reconstruction (see also Figure 0.3; after Accotto et al., 2020); (b) sketch of the outcrop showing reversed polarity and local SW vergence of the F1 structures.

6. D1 south-vergence in the Lalla Mimouna-Oued Awam inliers

(WGS84 UTM coordinates: 30S, 517250mE, 3764372mN)

In the Lalla Mimouna-Oued Awam inliers, the normal limb of a recumbent anticline is exposed. Along the dirt road connecting Lalla Mimouna to the other inliers there are

several outcrops. However, the exposure conditions are generally poor because of the mainly slaty nature of the DMMS in this area: S1, in fact, developed pervasively in the slaty beds with anastomosed geometries that complicate the interpretation of its geometric relationships with S0. Nevertheless, in the valley of the Oued Mechatta (tributary of the Oued Wizaght) there are a few sandy beds that preserve these relationships.

At site 6, a dm-thick sandy layer is folded and the geometric relationships between the bedding S0 and the S1 cleavage show local S-vergence (Figure 6a). Stratigraphic polarity indicators observed in other outcrops close to site 6 show normal polarity. Therefore, we are now walking on the normal limb of a recumbent S-vergent anticline (Figure 6b).

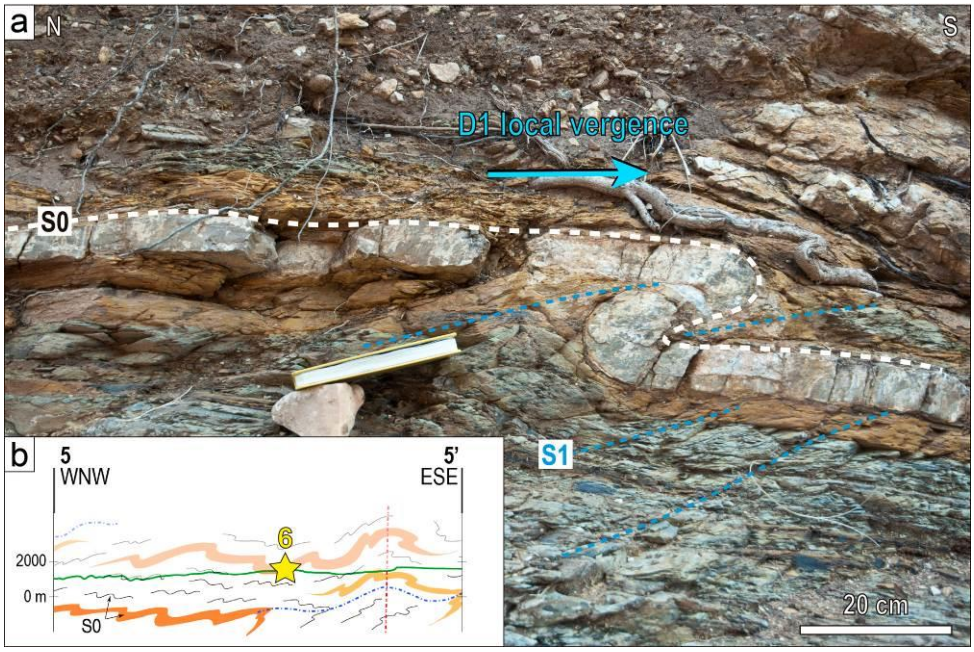

Figure 6: (a) sandy layer within the DMMS slates folded by the D1 event indicating S-vergence; (b) cross section showing the location of the stop within the regional-scale structural reconstruction (see also Figure 0.3; after Accotto et al., 2020).

7. Dc deformation in the Lalla Mimouna-Oued Awam inliers

(WGS84 UTM coordinates: 30S, 516859mE, 3763725mN)

Southwards following the Oued Mechatta, we can observe the increasing effects of the Dc deformation, in this area represented by m-scale upright chevron folds (Figure 7a) that deform the pre-existing S0 and S1 planar elements (the latter poorly exposed).

Along the Lalla Mimouna-Oued Awam inliers, the effects of the Dc deformational event increase considerably eastwards (Figure 7b).

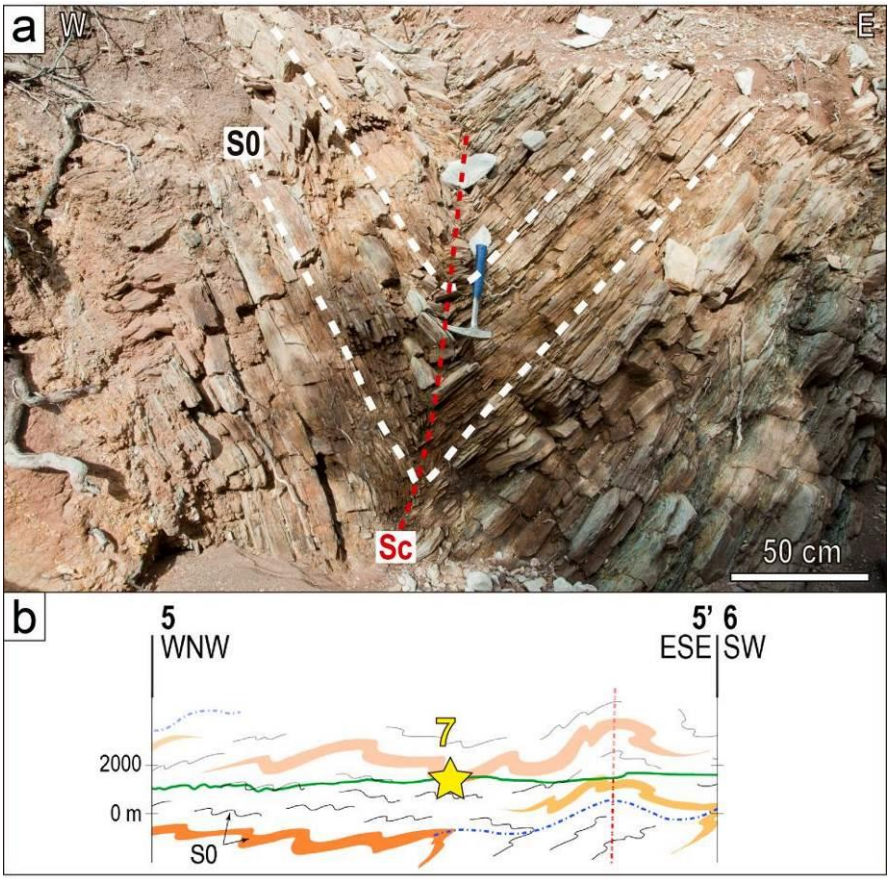

Figure 7: (a) Upright chevron folds related to the Dc deformational event.; (b) cross section showing the location of the stop within the regional-scale structural reconstruction (see also Figure 0.3; after Accotto et al., 2020).

8. Reverse limb and tectonic banding in Sidi Lahsene

(WGS84 UTM coordinates: 30S, 533229mE, 3774461mN)

Along the segment of the road P6003 that cross-cuts the Mekkam inlier, the relationships between S0 and S1 are commonly complicated or completely obliterated by the late crenulation event Dc. The structures related to this event are chevron and kink-band folds, as well as a well-developed spaced crenulation cleavage that locally is so intense to form a tectonic banding.

Moving towards Sidi Lahsene, at stop 8, the Dc folds are intense but they preserve the original relationships between S0 and S1 (Figure 8a). Here, the polarity of the beds is marked by downward fining of some beds, indicating reversed stratigraphic polarity (Figure 8b). The S1 surfaces appear to be refracted within the more competent parts of the beds, and their geometric relationships with the bedding indicate SW local vergences of the D1 structures (Figure 8b).

Altogether, these characteristics indicate that Stop 8 is located in the reverse limb of a recumbent D1 fold (Figure 8c).

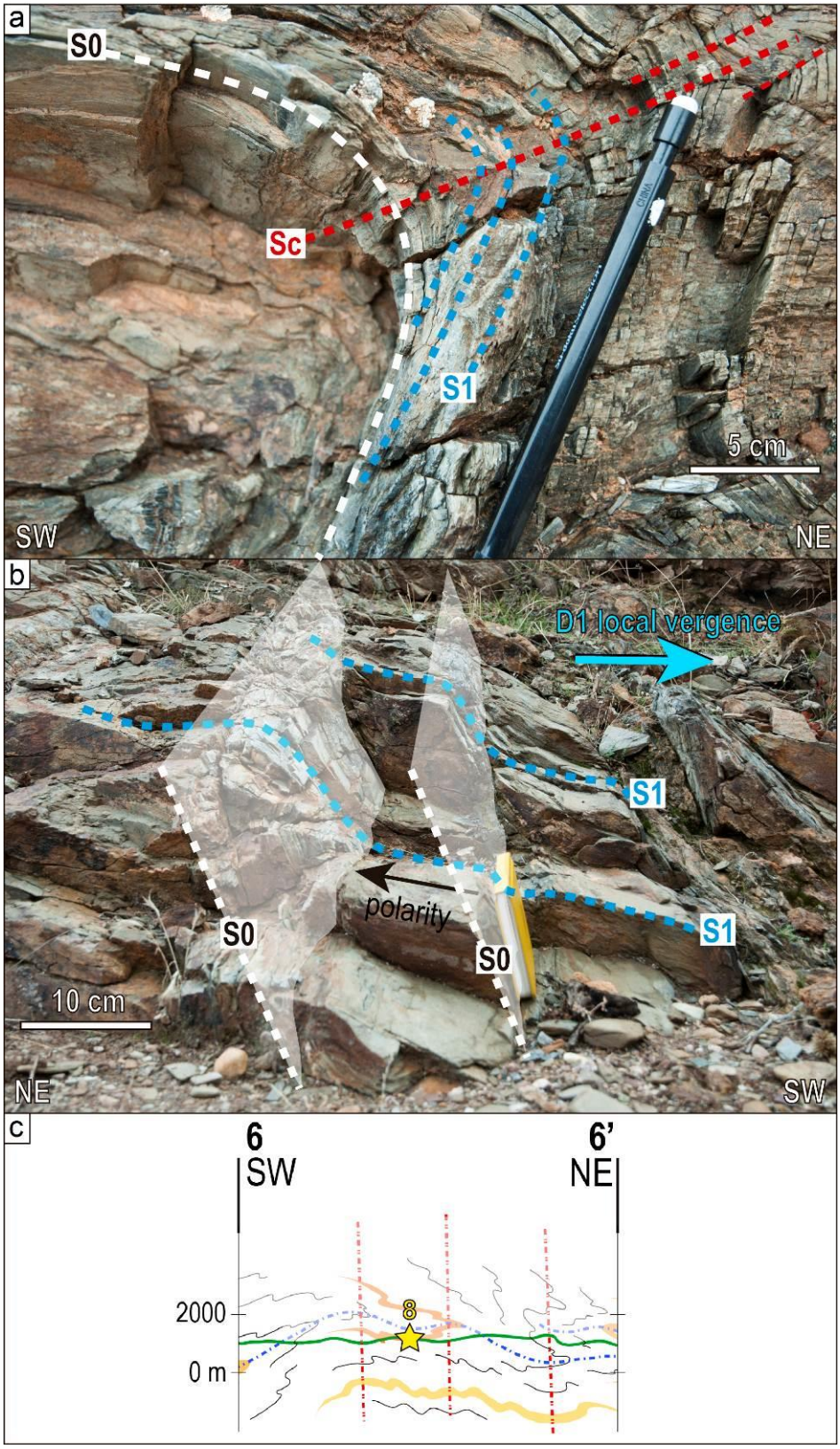

Figure 8: (a) dm-scale Fc folding of the pre-existing structures (S0 and S1) and development of a spaced crenulation cleavage of axial plane (Sc); (b): Relationships between the bedding S0, with reversed polarity, and the cleavage S1 refracted in the more competent layers; (c) cross section showing the location of the stop within the regional-scale structural reconstruction (see also Figure 0.3; after Accotto et al., 2020)

9. Normal limb of Sidi Lahsene

(WGS84 UTM coordinates: 30S, 541890mE, 3774441mN)

Continuing on the paved road from Sidi Lahsene to the East, we observe some very deformed outcrops where a sub-horizontal tectonic banding has obliterated all the previous structures. At Stop 9, the deformation is less intense. Along the road there are some poorly preserved cross laminations that suggest normal polarity. This stratigraphic polarity is confirmed by a better exposed outcrop along the river bed (Figure 9a), where the sandy layers fine upward.

The outcrop also shows clear S0/S1 geometric relationships indicating NE vergence of the D1 structures (Figure 9a). Altogether, these observations suggest that we are once again in the normal limb of a recumbent anticline (Figure 9b).

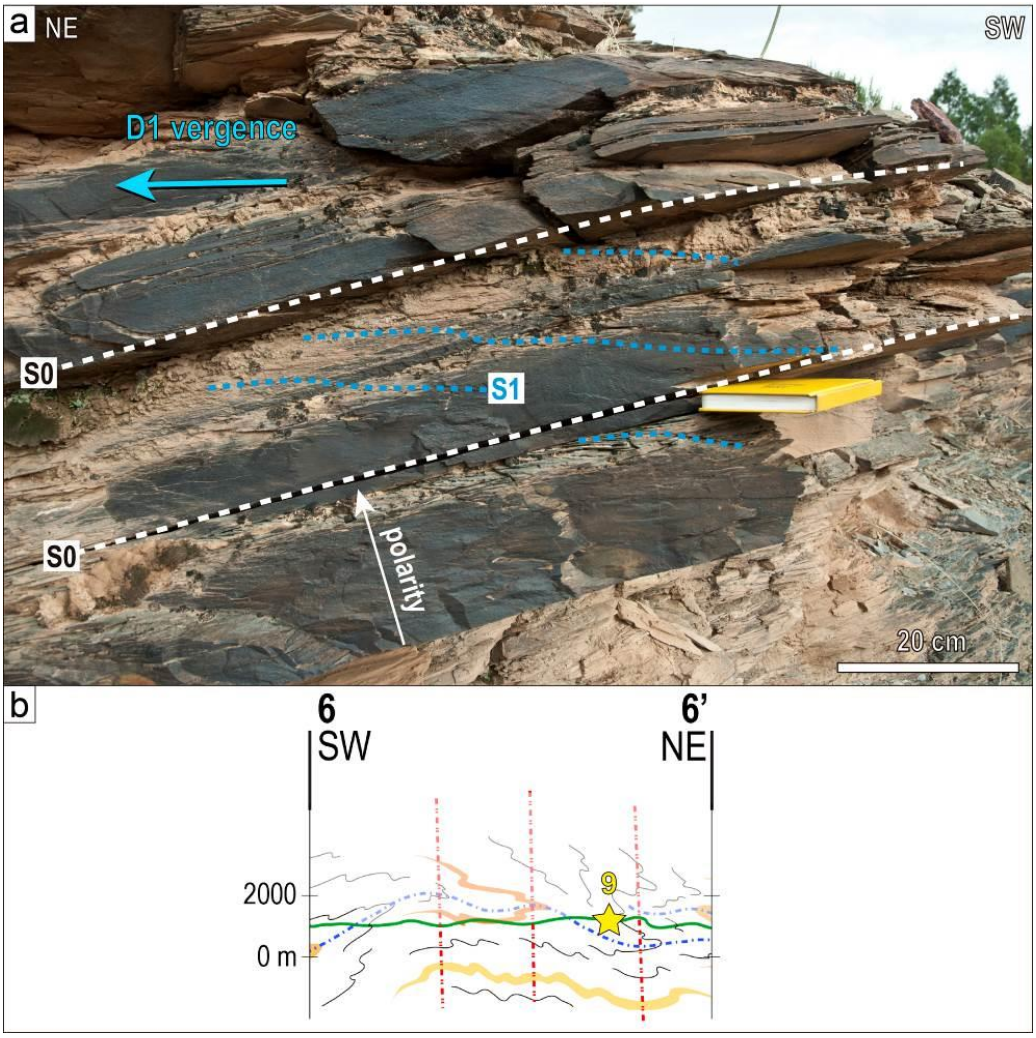

Figure 9: (a) Sandy and slaty layers showing normal stratigraphic polarity and S0/S1 geometric relationships indicating D1 vergence towards the NE; (b) cross section showing the location of the stop within the regional-scale structural reconstruction (see also Figure 0.3; after Accotto et al., 2020)

10. Upper Visean unconformity of Hassiane Ed Diab and timing of the deformational events

(WGS84 UTM coordinates: 30S, 532886mE, 3761758mN)

A dirt road departs toward the south from the mountain pass along the P6052, between the Oued Bezzouz valley and the plateau of Aïn Bni Mathar. The road follows the headwater of the Oued Bezzouz valley up to a small group of houses where it disappears.

Here, in the abundant stream incisions, the Upper Visean unconformity is exposed. The DMMS is exposed in the form of slates deformed by the D1 event into open to tight inclined folds (Figure 10). The S1 cleavage is locally observable.

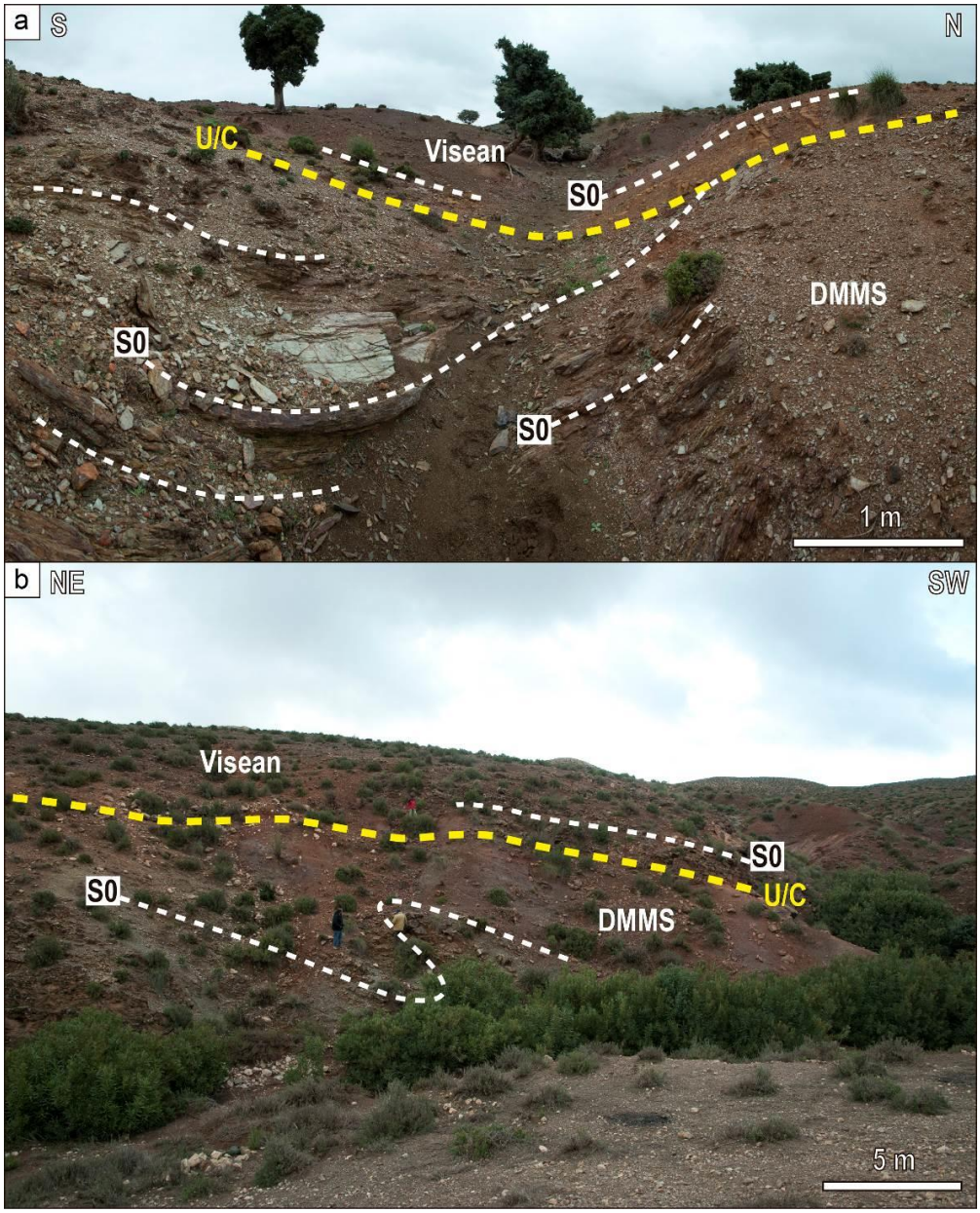

Figure 10: (a) and (b) two outcrops of the Late Visean sequence unconformably (U/C) overlying the DMMS.

The unconformity is marked by a level of up to 5 m of bioclastic limestones, dated at the Late Visean (Médioni, 1979 and references therein), followed by an hm-thick volcanoclastic sequence. Within the Visean sequence, there is no evidence of S1 and the only observable deformation structures are upright open Dc folds. The D1 deformational event, therefore, likely occurred before the deposition of the Late Visean sediments.

Detrital zircon geochronology was carried out on five samples of the DMMS from the Debdou, Lalla Mimouna-Oued Awam, and Mekkam inliers (Accotto et al., 2020). The results indicate that the maximum depositional age of these rocks is Late Famennian, which implies, therefore, that the D1 deformational event occurred between Tournaisian and Early Visean.

Acknowledgements

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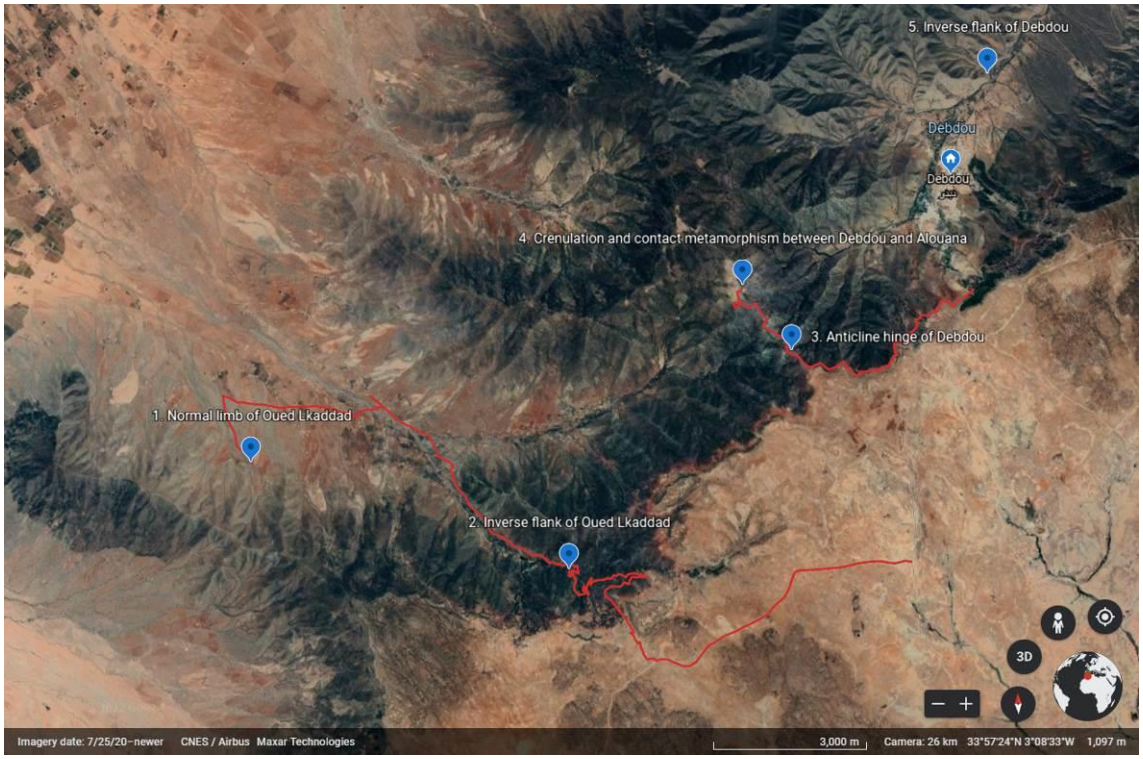
Appendix: How to reach some of the stops.

Dirt roads (in red in Map 1) locally in poor condition; a 4x4 vehicle is needed. It is not recommended to drive on it in the dark or during adverse weather events:

- **Point 1 from P5435**
  P5435 (from Taourirt, to the North, or from Mahirija, to the West)
- **Point 2 from N19**
  N19 (from Debdou, to the North)
- **Point 2 from P5435**
  P5435 (from Taourirt, to the North, or from Mahirija, to the West)
- **Points 3 and 4 from N19**
  N19 (from Debdou, to the North)

Access to **point 5**: **paved road** N19 to Debdou.



Map 1: access to points 1, 2, 3, 4, and 5 (from Google Earth).

Dirt roads (in red in Map 2) locally in poor condition; a 4x4 vehicle is needed. It is not recommended to drive on it in the dark or during adverse weather events:

- **Points 6 and 7 from P6052**
  P6052 (From Taourirt, to the West, or from Ain Beni Mathar, to the East)
- **Point 10 from P6052**
  P6052 (from Ain Beni Mathar, to the East, or Taourirt, to the West).

Path (vehicles are not allowed) to **Points 6 and 7:** Trail, stream bed, or meadows with shrubby vegetation. It is not recommended to walk it in the dark or during adverse weather events.

Paved roads:

- **Point 8 from P6003**
  P6003 (from Tancherfi, to the North, or from P6052, to the South)
- **Point 9 from P6003**
  P6003 (from Tancherfi, to the North, or from P6052, to the South)
- **Access to point 9 from P6048**
  P6048 (from Jerada, to the North, or from R606 and Ain Beni Mathar to the South)

Map 2: access to points 6, 7, 8, 9, and 10 (from Google Earth).

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