

The final closure of the Vardar Ocean: paleomagnetic, AMS and structural results

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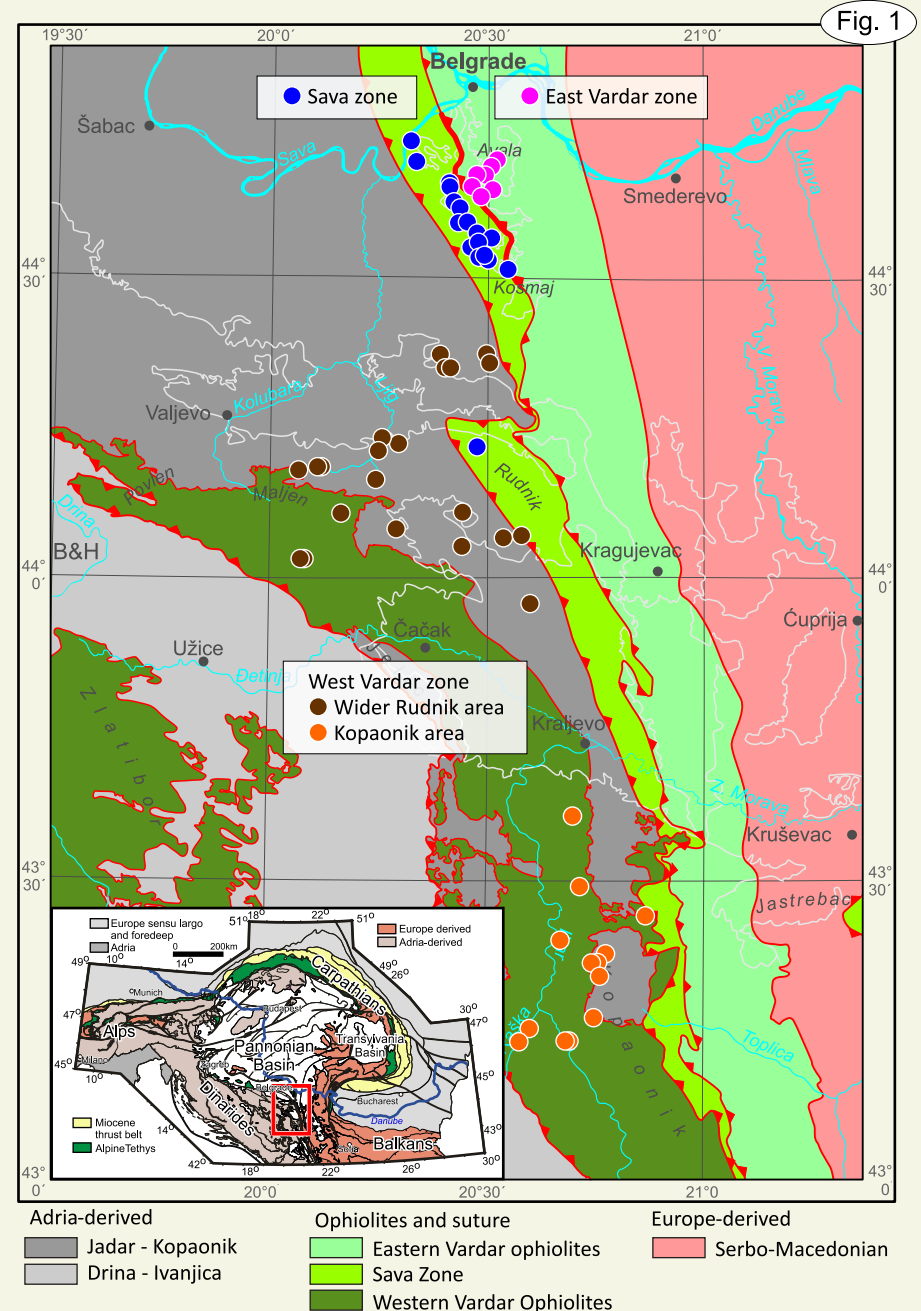
VARDAR ZONE GEOLOGICAL SETTING AND PALEOMAGNETIC SAMPLING LOCALITIES

The Vardar zone is a highly complicated suture between units of African and European affinities, which also contains remnants of an oceanic domain. This domain was characterized by extensional opening during the Triassic and Jurassic. In the Upper Jurassic, the oceanic lithosphere was obducted, simultaneously over the continental units of African and European origins, respectively.

The remnant of the oceanic crust, however, persisted in the Sava zone till the Late Cretaceous-Eocene continental collision. During the final closing, the flysch sediments of the Sava zone were trusted over by the sediments of the Eastern Vardar zone along a generally NNW-SSE trending fault system, which is called Bela Reka Fault (heavy red line) in the Belgrade area. The flysch of the Sava zone, in its turn was trusted over the Western Vardar zone.

During the Oligocene and Lower Miocene there was an intensive igneous activity in the Vardar zone. The products of this activity are widespread in the Eastern well as in the Western Vardar zone, while in the Sava zone they are known from a restricted area.

**AREA OF THE NEW INVESTIGATIONS:
SAVA ZONE AND EAST VARDAR ZONE
IN THE BELGRADE AREA.**



METHODS

COLLECTION AND EVALUATION OF STRUCTURAL AND KINEMATIC DATA

PALEOMAGNETIC SAMPLING

Sampling localities/sites

Eastern Vardar zone

- 4 Oligocene dykes
- 3 Upper Cretaceous shallow water carbonates

Bela Reka Fault zone

- 1 Upper Cretaceous marl

Sava zone, Upper Cretaceous flysch

- 2 marls from the S part intruded by Oligocene igneous rocks
- 14 marls from the area apparently devoid of Oligocene igneous rocks

Method of sampling

Taking cores with a gasoline powdered portable drill
Orientation in situ with magnetic or magnetic and sun compass
312 independently oriented samples in total

LABORATORY EXPERIMENTS

Measurements of the NRM in the natural state and after each demagnetization step

AMS measurement in the natural state

Stepwise AF or TH demagnetization

Monitoring of the susceptibility on TH demagnetization

Temperature versus susceptibility measurements (from liquid nitrogen temperature to 700°C)

IRM acquisition experiments and the stepwise TH demagnetization of the 3 component IRM accompanied by susceptibility monitoring

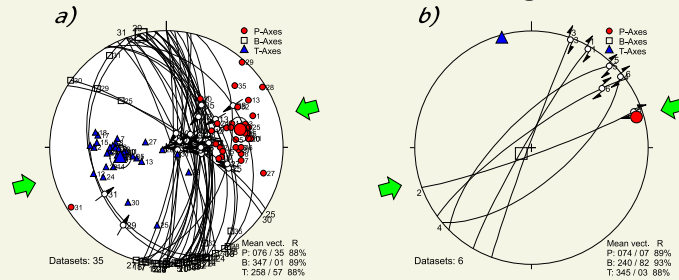
RESULTS

THERE IS A GENERAL CORRELATION BETWEEN STRAIN FIELD DIRECTION DURING LATE CRETACEOUS – EOCENE AND WELL DEFINED AMS LINEATIONS IN THE SAVA ZONE

DEFORMATION PHASES AFFECTING THE STUDY AREA

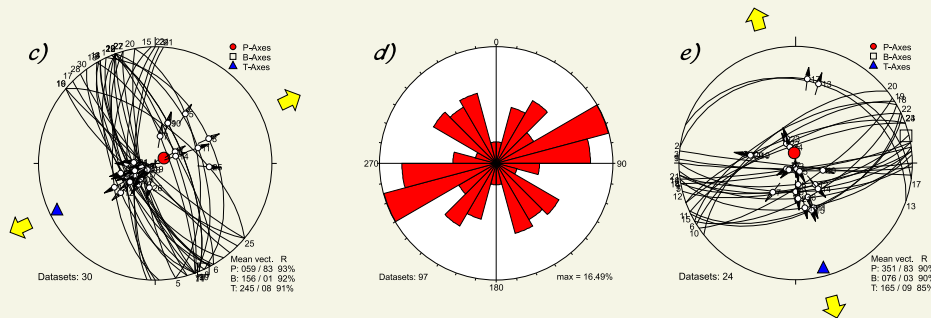
a) & b) Kinematic data for the **Late Cretaceous–Paleogene** shortening events

Fig. 2

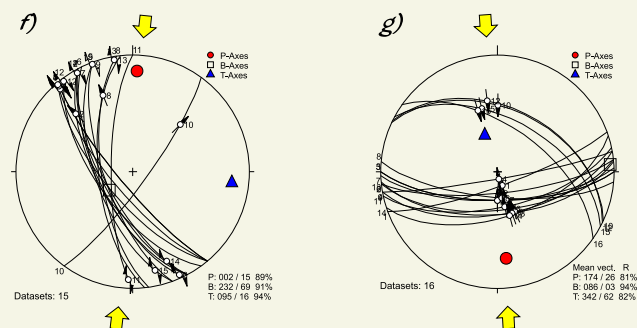


c) & e) Kinematic data for the **Oligocene–Miocene** phases of extension

d) Directions of Oligocene–Miocene dykes in vicinity of Belgrade.

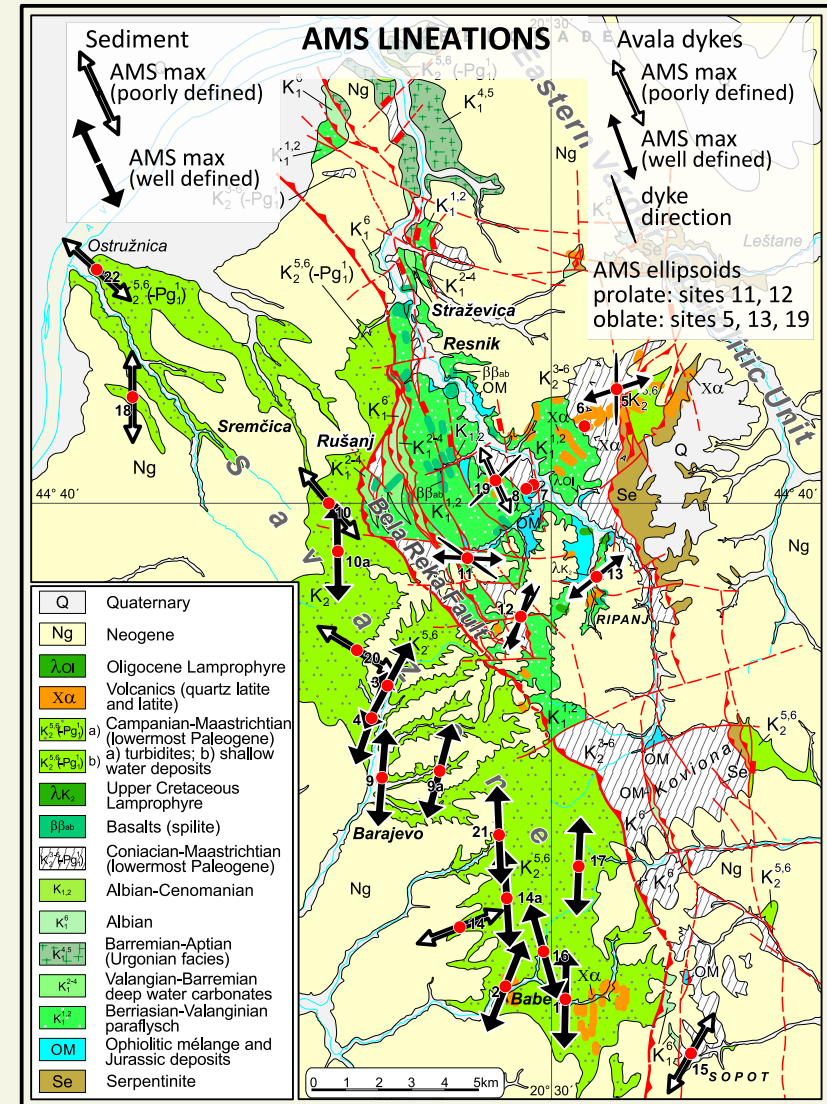


f) & g) Kinematic data for the **Late Neogene** shortening events



Lines with arrows are stereoplots of faults with sense of shear, derived from kinematic indicators (such as slickensides or Riedel shears).

Fig. 3



DETAILS CONCERNING AMS IN THE SAVA ZONE

Late Cretaceous marls: Mean susceptibility $129\text{--}346 \times 10^{-6}$ SI

Para + ferromagnetic minerals

For 10 localities in the middle and southern segments of the Sava zone
(when half cones of the error ellipsoid of AMS max $<15^\circ$) lineation is ~N-S oriented

Strain field character and direction from structural and kinematic observations

1. Phase: Late Cretaceous-Eocene $\approx$ **W-E compression**
2. Phase: Oligocene-Miocene **ENE-WSW extension**
NNW-SSE extension
3. Phase: Late Neogene **N-S compression**

AMS lineations imprinted before tilting of the strata, during 1st phase of deformation

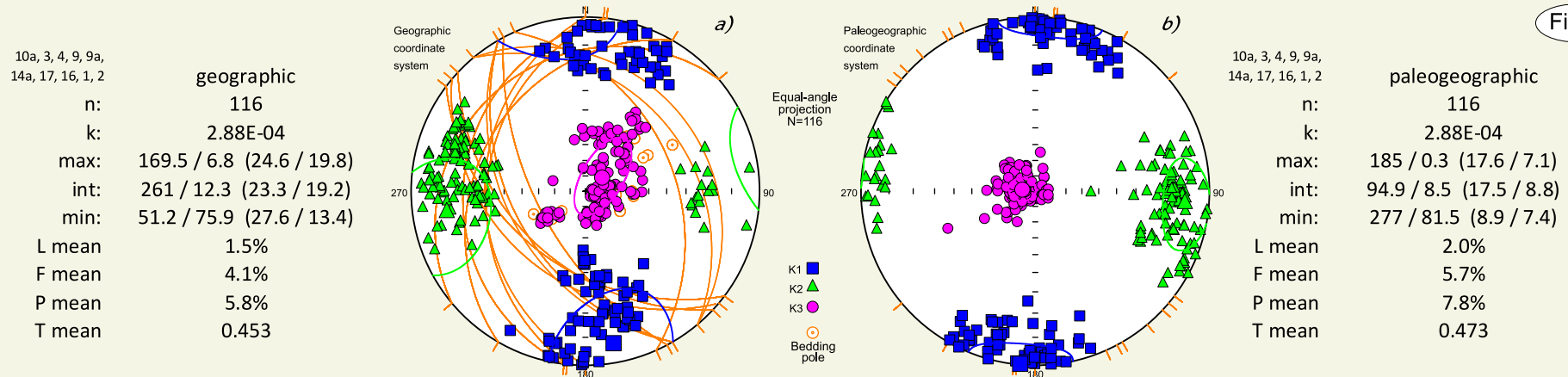


Fig. 4

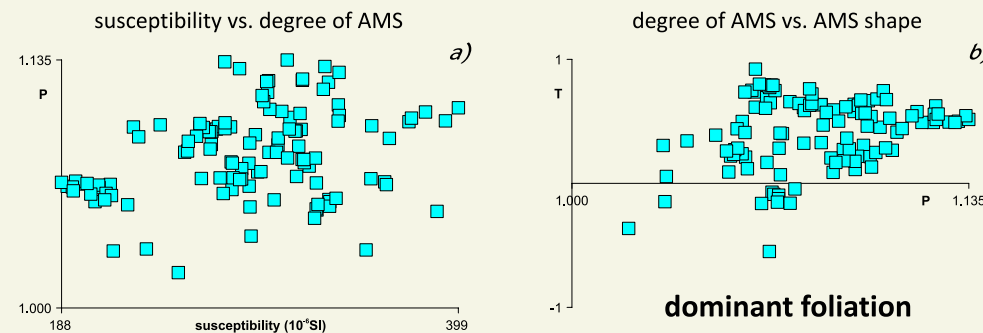


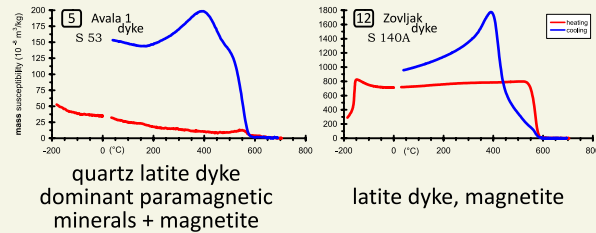
Fig. 5

The paramagnetic contribution to the susceptibility of the Upper Cretaceous marls is about 85-90%, according to the temperature vs. susceptibility measurements (Hrouda 1994, Chadima and Hrouda 2012)

MAGNETIC MINERALOGY AND DEMAGNETIZATION BEHAVIOUR

Identification of magnetic minerals: igneous rocks, Avala Mts. Temperature vs. magnetic susceptibility curves

Fig. 6

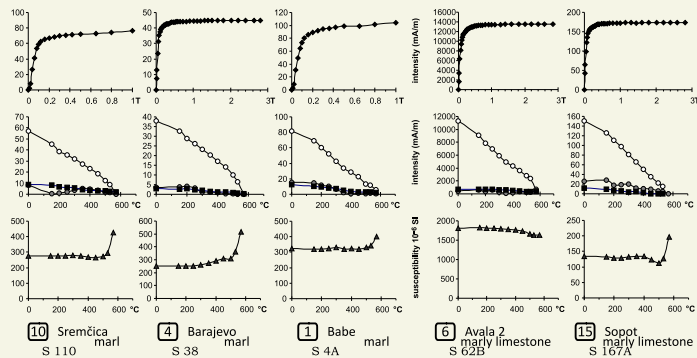


Identification of the magnetic minerals in Cretaceous sediments from the Belgrade area

Locality 6: Avala Mts. Shallow water carbonate; Locality 15: marl within the Bela Reka Fault system; Localities 10, 4 and 1: marls from the Sava zone.

From top to bottom: IRM acquisition, Thermal demagnetization of the three component IRM (method by Lowrie, 1990) and Susceptibility during heating. The components of the IRM were acquired in fields of 2.8 or 1.0 T (squares), 0.36 T (full circles) and 0.12 T (open circles).

Fig. 7



dominant soft mineral ➡ magnetite

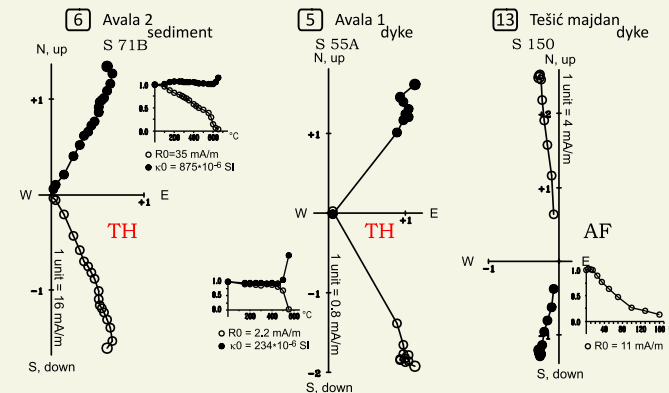
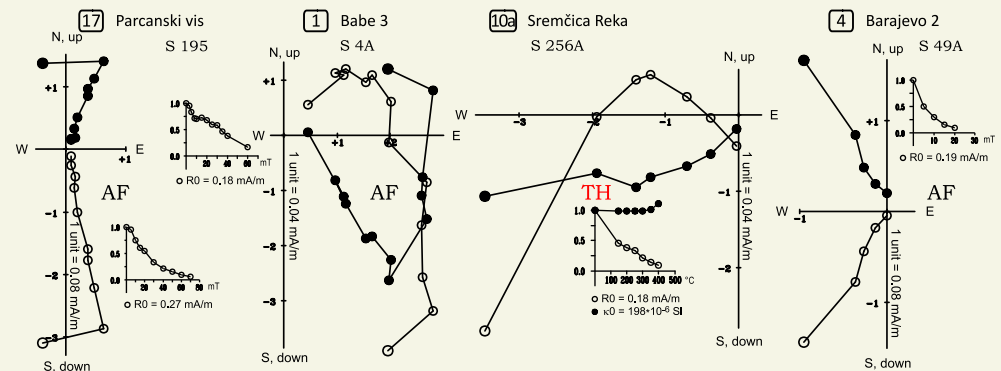


Fig. 8

Belgrade area, typical demagnetization curves. Locality 6: Upper Cretaceous shallow water carbonates. Sites 5 and 13: latite dykes. Localities 17, 1, 10a and 4: Upper Cretaceous marls.

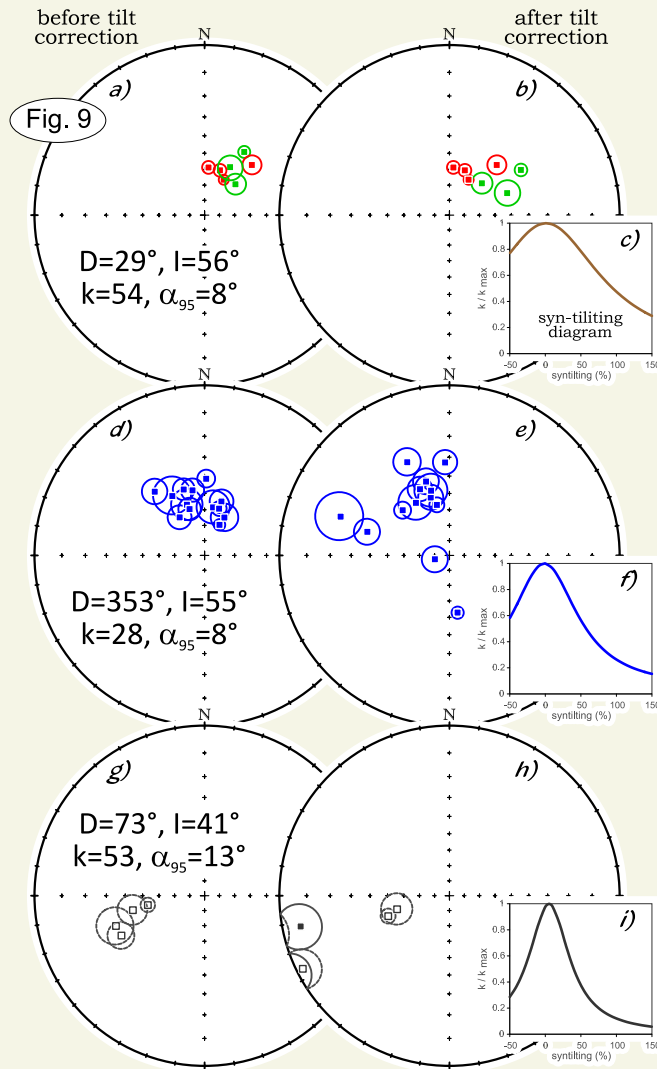
Key: The Zijderveld diagrams are in the geographic reference frame and accompanied by intensity (circles) versus demagnetizing field diagrams, when the method of demagnetization is AF, and by NRM intensity (circles) / susceptibility (dots) versus temperature diagrams, when the method of demagnetization is thermal. In the Zijderveld diagrams, full dots are the projections of the NRM vector onto the horizontal, circles: into the vertical.

E Vardar zone: basically single component NRM, the dykes as well as the sediments



Late Cretaceous marls: single component or more often composite NRM

FIELD TESTS TO CONSTRAIN THE AGE OF THE CHRM RELATIVE TO FOLDING/TILTING



Stereographic projections, locality/site mean paleomagnetic directions with α_{95} .

E Vardar zone (Avala Mts)

Dykes:

3 N, 1 R polarity, interpreted as primary magnetizations

Shallow water limestones:

N polarity, remagnetized during Oligocene igneous activity

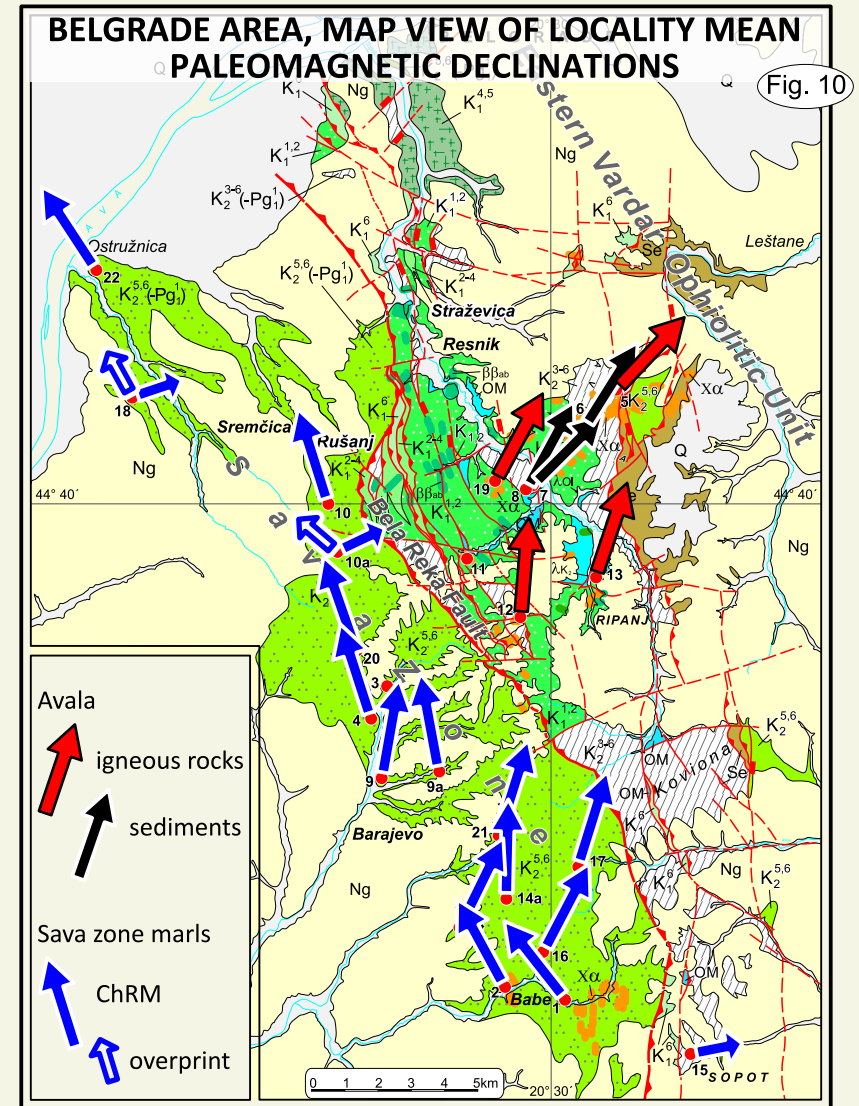
Sava zone

1st group:

12 N polarity, 1 R polarity

2nd group:

4 R polarity
Localities 18, 10a, 15 plus a single locality S of the Belgrade area (Fig. 1)
Enigmatic results, so far no tectonic interpretation



POSSIBLE TIMES/EVENTS FOR REMAGNETIZATION IN THE SAVA ZONE

ALTERNATIVES FOR THE TECTONIC INTERPRETATION OF THE PALEOMAGNETIC DIRECTIONS FROM THE SAVA ZONE

1st group of localities (Fig 9)

A) POSTDATES, B) AND C) PREDATE THE POST-OLIGOCENE CW ROTATION OBSERVED IN THE W AND E VARDAR ZONES

Arguments for and against the three alternatives

A) Final uplift during the latest Neogene - beginning of Quaternary.	For A: Closeness of the overall-mean direction (Fig. 9) to the present local direction of the Earth magnetic dipole field Against A: Remagnetization during uplift is expected to produce e.g. goethite, hematite, which are not indicated (Figs. 7 & 8).
B) Oligocene igneous activity, including elevated temperature and hydrothermal fluids, restricted to the S part of the presently studied segment of the Sava zone.	For B: Some of the ChRMs clustering in the S part of the Sava zone have easterly declinations suggesting remagnetization during Oligocene volcanism Against B: ChRM for two localities (1 and 2, Fig. 10) in the Babe area have westerly declinations, although they are the closest ones to mapped igneous bodies. Overprint on them, however, would fit the pattern of moderate CW rotation.
C) Final phase of collision during Eocene, when the contents of the suture zone are buried deeper into the subduction zone. This process was responsible e.g. for metamorphism in the Kopaonik area (Fig. 1, Schefer et al., 2010).	For C: The marls sampled are dark grey, fresh looking, the magnetic mineral is magnetite sometimes accompanied by pyrite – environment indicated fits burial to moderate depth Against C: The same as argument for A.

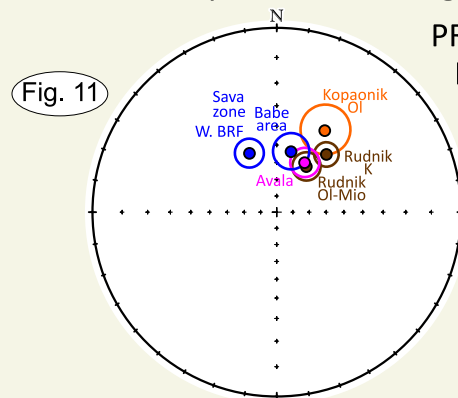
SUMMARY

TECTONIC INTERPRETATION OF THE PALEOMAGNETIC RESULTS FROM THE VARDAR ZONE

- **WESTERN and EASTERN VARDAR ZONES:** REMAGNETIZED PRE-OLIGOCENE SEDIMENTS and OLIGOCENE IGNEOUS ROCKS suggest about 30° VERTICAL AXIS CW ROTATION AFTER OLIGOCENE.
- **SAVA ZONE:** UPPER CRETACEOUS FLYSCH SEDIMENTS: POST-FOLDINGS/TILTING remanence
MAJORITY OF PALEOMAGNETIC DIRECTIONS (1st group, Fig. 9):

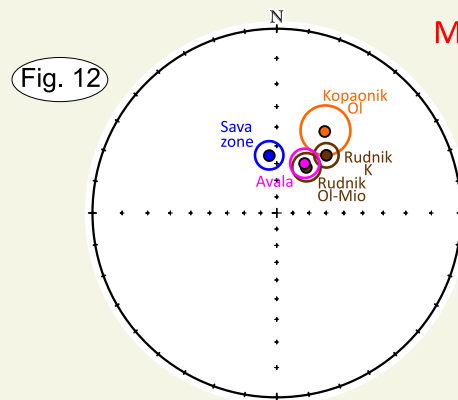
A - acquisition after Oligocene CW rotation, NO CONSEQUENCE FOR THE CLOSING OF THE SAVA ZONE

B - sediments of S part of Sava zone: EOCENE plus Oligocene re-magnetization
further to N only Eocene re-magnetization



PROBLEMATIC, based on the possible influence by
HEATING OR HYDROTHERMAL ALTERATION BY
POSSIBLY EXISTING, BUT NOT MAPPED INTRUSIONS

C - all localities of group 1 were essentially remagnetized during Eocene burial



MOST LIKELY OPTION –
IMPLIES A PRE-OLIGOCENE 30-40° CCW VERTICAL AXIS ROTATION
OF THE SAVA ZONE DURING THE FINAL CLOSING OF THE
VARDAR ZONE together with the EASTERN VARDAR ZONE,
ALREADY THRUSTED OVER THE SAVA ZONE

SUMMARY

MAGNETIC ANISOTROPY AND DEFORMATION

- AMS ELLIPSOIDS for dykes from the E Vardar zone are either oblate or prolate, K1 does not exhibit a regular pattern
- AMS ELLIPSOIDS for the Upper Cretaceous sediments of the SAVA ZONE ARE OBLATE, mostly have WELL-DEFINED AMS LINEATIONS, imprinted while the marls were still in horizontal position.
- There is a good GENERAL CORRELATION between K1 and the DIRECTION OF COMPRESSION DURING LATE CRETACEOUS-EOCENE thus **K1 MUST BE OF DEFORMATIONAL ORIGIN.**
- TAKING INTO ACCOUNT THE WELL DOCUMENTED POST-OLIGOCENE CW ROTATION, THE DIRECTIONS OF THE EXTENSION DURING OLIGOCENE-MIOCENE MUST HAVE BEEN NNE-SSW AND NW-SE, RESPECTIVELY. THE DIRECTION OF THE COMPRESSION DURING THE LATE CRETACEOUS-EOCENE DOES NOT NEED CORRECTION IN CASE OF ALTERNATIVE C (Fig. 12), SINCE THE CCW ROTATION WAS OF ROUGHLY EQUAL MAGNITUDE AS THE POST-OLIGOCENE CW ROTATION.

Acknowledgement

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