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Paleomagnetic analysis from the Balzes anticline (Southern Pyrenees): vertical-axis rotations and kinematics implications

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Abstract: The Balzes anticline is a complex structure outcropping in the eastern part of the External Sierras (southwestern Pyrenees). It is a representative oblique structure of this area, where many N-S trending anticlines are parallel to the main stretching direction. Paleomagnetic analyses allow a preliminary kinematics model to be proposed for this structure. Twelve paleomagnetic sites (mostly derived from magnetostratigraphic analysis) were sampled to calculate rotation magnitudes in both anticline limbs. A Characteristic paleomagnetic component, deduced from detailed TH and AF demagnetizations, unblocks up to 570 °C. Rotation ranges from 33° clockwise (CW) to 18º counterclockwise (CCW) are detected with a primary signal (with inclination error). This preliminary dataset permits us to propose a new geometric and kinematics model; the effect of the sedimentary wedge (decreasing southwards) together with E-W fold interference, a slow lateral transference of the deformation (rotation) and the low angle thrusting, generate a conical anticline in its northern part passing to a cylindrical structure southwards. This preliminary model will be improved by a denser network of paleomagnetic, seismic, structural and stratigraphic data, which will lead us to determine the geometry and kinematics of this anticline.

Keywords: Balzes anticline, External Sierras, Pyrenees, paleomagnetism, fold and thrust belts, conical fold.

The Balzes anticline is the southeasternmost structure of the External Sierras front in the Southern Pyrenees. Along with the Boltaña anticline, it represents a set of important oblique structures between the Jaca and Ainsa basins, being a key area of lateral transference of deformation (Fig. 1). The Balzes anticline formed mainly during Middle Eocene times (Millán, 1996; Barnolas and Gil-Peña, 2001), a key period in the configuration of the South Pyrenean marine basins.

Previous paleomagnetic and structural studies in the area show important clockwise rotations and the transference of deformation in a western direction (Millán *et al.*, 2000; Fernández, 2004). Up to 50-70° clockwise rotations were found in Ypresian rocks (Ilerdian-Cuisian) in the Boltaña anticline (Dinarès, 1992; Fernández, 2004) and 45° in the Lower and Middle Lutetian slope deposits (Mochales *et al.*, *in press*). Magnitudes of clockwise (CW) rotation of about 15-20° in Upper Lutetian-Bartonian deltaic deposits of the eastern limb of Boltaña anticline (Bentham, 1992) and Bartonian deltaic deposits of the western limb display 40° of CW rotation (Pueyo, 2000). The Balzes anticline remains unexplored from this point of view and represents an excellent case-

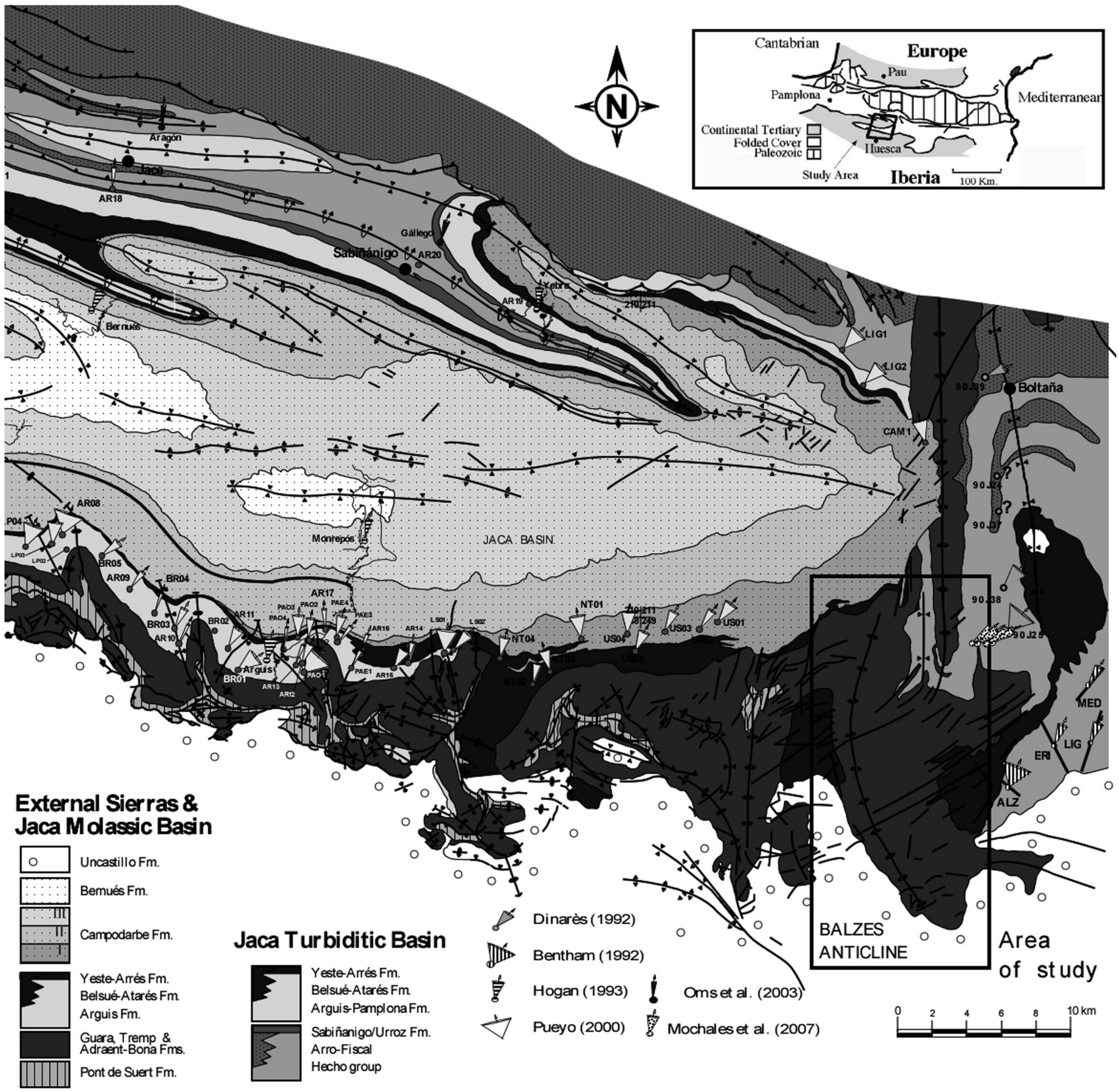

Figure 1. Geological sketch map; data by Puigdefábregas (1975), modified by Millán (1996, 2006) and Pueyo (2000). Rotation magnitudes in eastern Jaca basin.

study of oblique and curved structures. An exhaustive magnetostratigraphic study carried out in the syntectonic sedimentary rocks (Cuisian-Lutetian gap) has been developed (Rodríguez *et al.*, 2007) aiming for: 1) an accurate timing of the deformation (folding and thrusting) in the area, and 2) the quantification (and dating) of the rotation values. This work shows the rotational data acquired from the analysis of two long magnetostratigraphic profiles (more than 1200 m of pile) that have been regrouped in 11 sites (subsets), plus one additional site (more than 400 studied samples in total).

Geological setting

The Balzes anticline together with the Boltaña anticline represents the westernmost portion of the South Pyrenean Central Unit, mostly built up of E-W trending folds in its frontal structures (i.e. Sierras Marginales, Montsec). The stratigraphic pile involved in the BA is made of shallow marine platform limestones and marls (Ilerdian to Bartonian times); the main thickness corresponds to the Alveoline limestones of the Boltaña and Guara Formations (Cuisian-Lutetian). It is a 17 km long arched anticline

(Fig. 1) and the fold hinge trends N015E in the northern sector passing to N150E in the southernmost sector, therefore, in map-view it displays an apparent bending of about 45° (southwestwards convex). The northernmost outcrops seems seem to plunge slightly to the north as the result of the moderate northwards tilting of the dorsal-wall located over the Pyrenean sole thrust underneath. The anticline finishes in a smooth fold-closure in its southernmost portion, which is partially fossilized by Upper Oligocene-Lower Miocene conglomerates. A well-preserved progressive unconformity in the northern sector reveals the major folding event during Middle Lutetian time (Barnolas and Gil-Peña, 2001). A second stage of underneath thrusting happened during Chattian-Burdigalian times (Millán *et al.*, 2000).

Paleomagnetic data

Sampling

Two long magnetostratigraphic sections were densely sampled (5-10 samples each 10 m) in the Balzes anticline (Fig. 2): 1) the Meson de Sivil (SIV) section (570 m) in the southeastern limb throught the Cuisian and Lower Lutetian (Boltaña and lower Guara Formations) and 2) the Santa Marina de Bagüeste (BZ) section (650 m) in the northernmost outcrops across the Lutetian progressive unconformity (Guara Formation). These profiles have been processed in discrete subsets allowing eleven robust rotation values to be acquired (6 in BZ and 5 in SIV). An additional discrete site (SS) in the Lutetian carbonate slope facies located over the eastern limb (Sarsa de Surta area) was sampled in order to perform the fold test in the northern section. In total, more than 400 standard cores were directly drilled and *in situ* orientated during the fieldwork.

Laboratory procedures

Detailed progressive demagnetization was performed to unravel the NRM components. 227 samples were demagnetized by alternating field (AF) and 456 specimens by thermal treatment (TH) at intervals of 5-20 mT and 25-50 °C respectively. Some magnetic min-

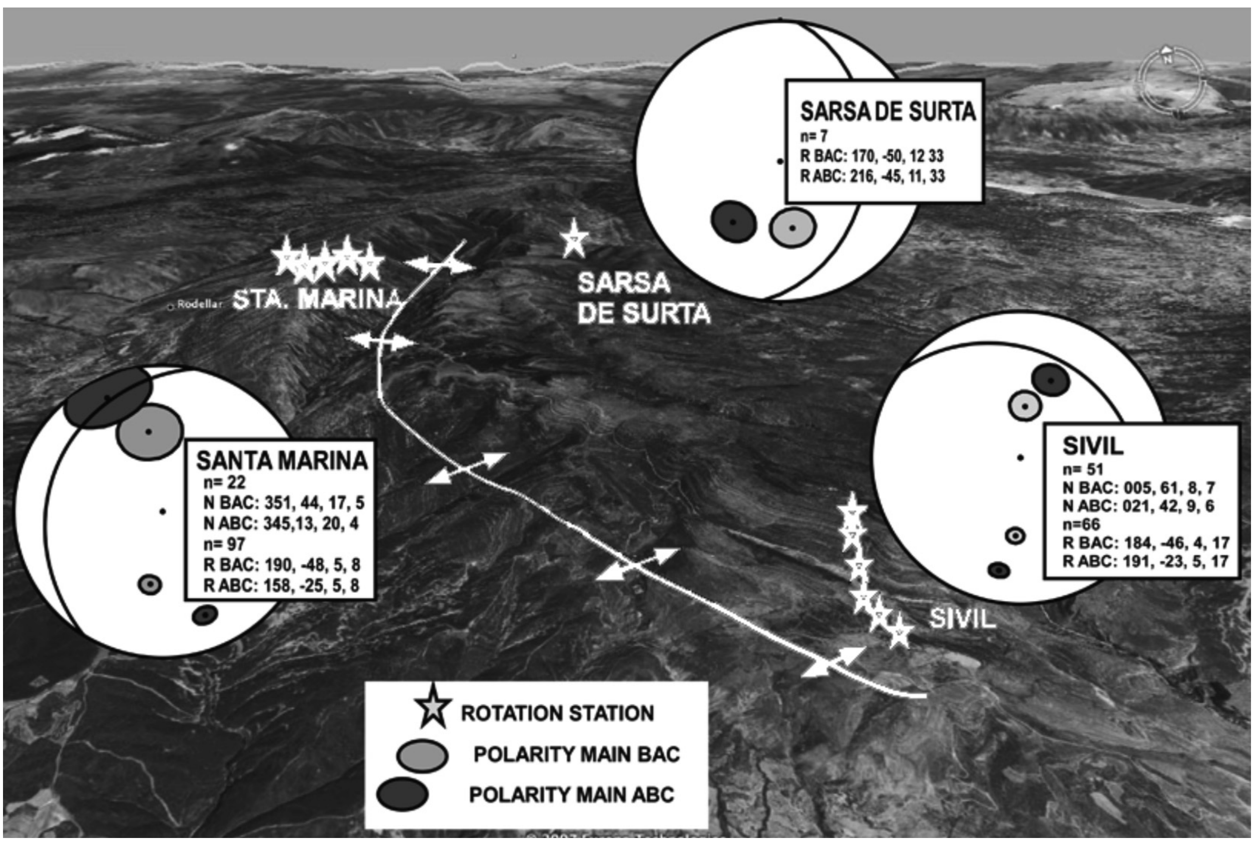

Figure 2. Balzes anticline rotation magnitudes. Locations of the sampling profiles and the stereographic means before and after bedding correction (gray and black respectively). Great circles represent the mean bedding plane in each location.

eralogy experiments, including IRM and thermal demagnetization of a three-component IRM, were also carried out. The measurements were conducted in the University of Burgos and in the Fort Hoofddijk (University of Utrecht) paleomagnetic laboratories by means of a 2G cryogenic magnetometer, a TD-48 SC (ASC) oven, a laboratory made oven (Utrecht), and a M2T-1 pulse magnetizer. Susceptibility measurements were carried out with a KLY-4 during the thermal treatment to check possible mineralogical changes.

Samples were classified as regards the quality of their characteristic directions. For a structural study like this, only the best-quality samples were considered: well-defined and stable directions (defined by more than 5 steps) and demagnetization circles (arc fragments defined by 4 steps or more). The directions and demagnetization circles were fitted by means of the

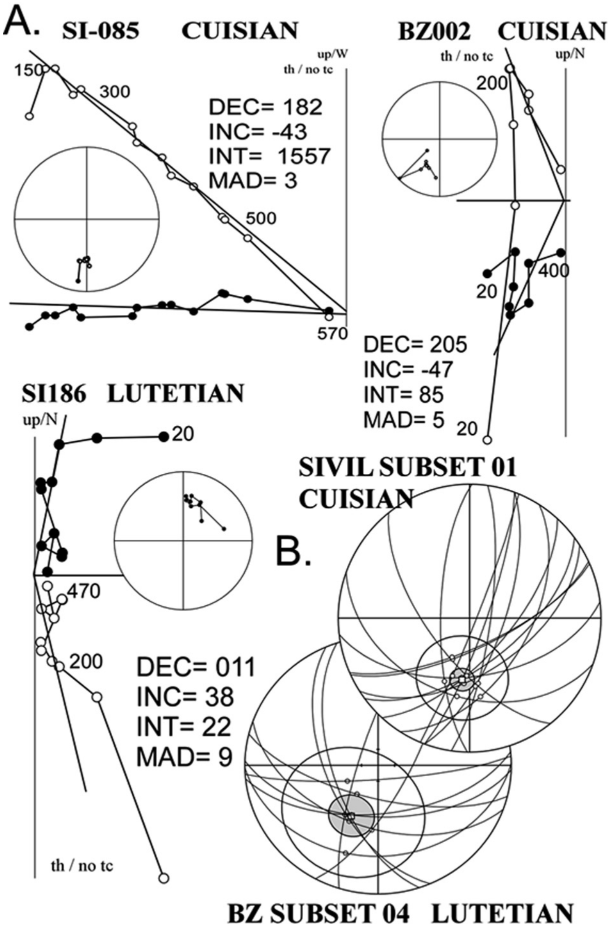

Figure 3. Demagnetization diagrams and site mean values. A) Zijderveld Diagrams and stereograms showing characteristic Cuisian and Lutetian, normal and reverse directions, B) combined technique of demagnetization circles and PCA directions in SI and BZ subsets.

Paldir program (University of Utrecht). The directions (direct observations) were calculated by principal component analysis, PCA (Kirschvink, 1980), and the application of the demagnetization circles observations was approached by means of the combined analysis of direct observations (directions) and demagnetization circle (McFadden and McElhinny, 1988) using the Palfit software (University of Utrecht). The ABC mean values were calculated in Stereonet software using Fisher statistics (Fisher, 1953) as the BAC mean values.

Mineralogy and components

Besides recent overprints at low temperatures (20 °C up to 250 °C), a main characteristic paleomagnetic component can be distinguished and unblocks from 200-250 °C up to 450-575 °C. This component presents two pseudoantipodal polarities, depending on the case (Fig. 3), and seems from being a reliable record of the Eocene magnetic field. In general, de NRM is weak (5×10^{-5} A m^{-1}), but it does not prevent the primary component to be calculated. In some cases, the Cuisian rocks display unblocking temperatures higher than 575 °C due to the occurrence of hematite (hard coercivity mineral), though magnetite is the main carrier. Lutetian rocks also have magnetite as a main carrier and an important quantity of undifferentiated sulfides in most of the samples.

Paleomagnetic stability

The characteristic directions obtained in the Balzes anticline (Fig. 2) present two pseudo-antipodal polarities that have allowed the building of a reliable sequence of the inversions after comparing to the Eocene magnetic polarity time scale (Cande and Kent, 1992). This calibration is also consistent with the available biostratigraphic data. Therefore, they could be considered as a primary record of the Eocene field. However, an inclination shallowing is patent in the magnetostratigraphic profiles, whereas the SS site displays a reasonable inclination. The inclination errors warn us of a possible external source of error that could deflect the original magnetic record orientation producing the pseudo-antiparallelism. Besides a potential inclination flattening, the overlapping of primary or secondary components could seriously deflect the expected paleomagnetic mean orientation (Rodriguez-Pintó *et al., in review* a, b). The limited size of the current dataset and the complexity of the structure do not allow any significant further checking (such as the fold test). At any rate, this issue will certainly be addressed

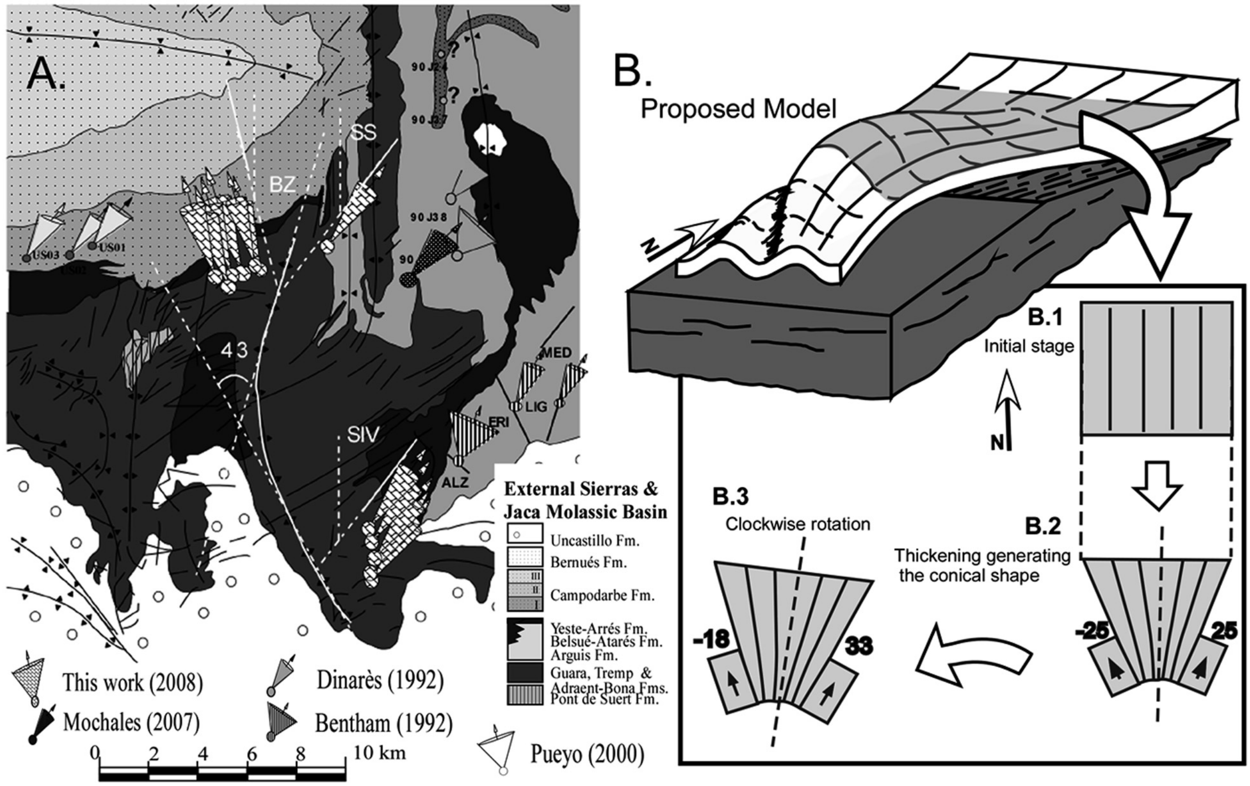

Figure 4. A) Rotation magnitudes in the Balzes anticline, additional data from other authors in the surrounding areas are also displayed. Axes of cones represent the magnetic declination (after bedding correction) and the cone semiapical angle is the α_{95} value, B) preliminary kinematic model proposed for the Balzes anticline displaying a qualitative fold reconstruction. Map-view diagrams represent the rotational evolution of the structure.

in future and more detailed researche (i.e. a denser network of rotation control-points).

Kinematic constraints and structural model

A reference direction (DEC = 004, INC = -53, α_{95} = 6, k = 9, by Taberner *et al.,* 1999) is available in the eastern Pyrenean foreland basin. The contrasting of the local data (after bedding correction ABC) against this reference allows us to define the local rotation magnitudes. In the eastern limb, the SI mean value displays 21° CW rotation; similarly, the SS site shows 32° CW rotation, but the western limb by contrast displays 18° counterclockwise (CCW) rotation.

Although data are limited and must be considered with caution, a preliminary interpretation and a kinematics model proposal can be based on the following observations:

1) The northern sector of the anticline displays substantial differences in the declination record; about 50° of differential shortening.

2) This record is asymmetrical with respect to the paleomagnetic reference but symmetrical with respect to the fold axis orientation in this sector.

3) The differential rotation along the fold curvature observed in the eastern limb hardly exceeds 10°.

4) The fold axis pathway displays a bending of about 43°.

5) The wavelength of the northern structures is larger than for the southern ones.

6) The sedimentary thickness diminishes southwards.

The northern part of the Balzes anticline has a conical shape, probably due to both the thickening of the Eocene stratigraphic sequence to the north and fold interference with E-W (Pyrenean) main fold direction (the Guarga syncline complex). This conical geometry in the northern part (apex points southwards) requires a bulk vertical axis rotation of about 50°, but is actually accommodated by a different sense of rotation in every limb (about 25°): CCW in the western limb, CW in the eastern one. The present difference between both limbs is probably due to a moderate bulk CW rotation (≈10°) causing a final larger rotation in the eastern limb (32º) than in the western limb.

This later bulk rotation is probably possible in the nearness of the footwall ramp (Fig. 4), while the southern part of the Balzes anticline, located over the footwall ramp, is unable to rotate and the aforementioned bulk rotation is not significant. Therefore, the observed CW rotation (21º) must be acquired at the beginning of the deformation (Lutetian times) during the folding.

These new results differ substantially from other N-S structures in the area (i.e. Boltaña and Pico del Águila anticlines) where similar rotation values were found in both limbs (≈50° in Boltaña and ≈35° in Pico del Águila). In those structures, the present orientation is a secondary attribute caused by the regional gradients of shortening (Fernández, 2004; Rodríguez-Pintó *et al.*, *2008*). On the other hand, in the Balzes anticline, most of the observed bending seems to be a primary feature that has been slightly rotated (≈25°) during the deformation.

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