



Tectonics

RESEARCH ARTICLE

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Special Section:

Geodynamics, Crustal and Lithospheric Tectonics, and active deformation in the Mediterranean Regions (A tribute to Prof. Renato Funicello)

Key Points:

- New paleomagnetic data from Sicily are obtained to understand if CW rotations are due to thrust or strike-slip tectonics
- Dextral strike-slip faults of Mt. Kumeta and Rocca Busambra give 20–40° CW rotations that fade out at only 200 m from fault planes
- The 130 to 10° CW rotation of Sicilian nappes was due to rotational thrust-sheet emplacement during forward orogenic propagation

Supporting Information:

- Supporting Information S1
- Data Set S1
- Table S1
- Table S2

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Understanding Paleomagnetic Rotations in Sicily: Thrust Versus Strike-Slip Tectonics

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Abstract The paleomagnetic investigation of the western Sicily Maghrebic belt has revealed since the 1970s that large clockwise rotations up to 140° with respect to the Hyblean-African foreland occurred synchronous with Tertiary shortening of the chain. The observation that rotations decrease stepwise from internal to external tectono-stratigraphic units led in the 1990s to a widely accepted model postulating that rotational thrust-sheet emplacement during forward orogenic propagation. More recently, other authors suggested that clockwise rotations from Sicily are conversely the result of late orogenic dextral strike-slip tectonics. Here we report on a paleomagnetic investigation of 30 Jurassic-Eocene sedimentary sites sampled mainly across the WNW-ESE Mt. Kumeta and Rocca Busambra ridges (Trapanese Unit), both bounded to the north by high-angle reverse faults with dextral strike-slip components. We find rotations of 110°–120° at faults of northern ridge margins, which decrease to 80°–90° at ~200 m to the south and rise again moving further south. Thus, an excess rotation of 20°–40° due to dextral-strike-slip shear is annulled to the regional rotational background of the Trapanese Unit at only 200 m from fault traces, translating to paleomagnetically calculated strike-slip offsets not exceeding 600 m. Further north, seven sites sampled in the Imerese Unit, tectonically stacked above the Trapanese Unit, yield a ~130° rotation. Thus, our data confirm that CW rotations in Sicily are predominantly related to thrust-sheet emplacement. Strike-slip tectonics has very limited relevance and gives local rotations that fade out at only 200 m from fault planes.

1. Introduction

Paleomagnetic data may represent important tools to constrain mountain belt tectonics. Thrust sheets emplacing with a rotational component form curved mountain fronts at different scales, from hundreds of meters to thousands of kilometers (Cifelli & Mattei, 2010; Johnston et al., 2013; Macedo & Marshak, 1999; Maffione et al., 2009; Shaanan et al., 2015; Weil et al., 2010). In such settings, paleomagnetic rotation values are constant over wide sectors of the same nappe and vary progressively following changes of curved front trend. On the other hand, strike-slip faults yield rotations that peak at maximum values along fault trace and decrease—progressively or stepwise—moving away from it (Kimura et al., 2011; Sonder et al., 1994). The width of the rotation zone straddling the fault varies from hundreds of meters to few tens of kilometers and is a function of fault length, total displacement, locking of the fault zone, and crust rheology (Hernandez-Moreno et al., 2014, 2016; Kimura et al., 2011; Lamb, 1987; McKenzie & Jackson, 1986; Randall et al., 2011; Sonder et al., 1994).

Obviously, understanding the tectonics of orogenic rotations depends both on the availability of detailed structural evidence and on paleomagnetic data resolution across the chain. Unfortunately, a high paleomagnetic resolution (several sites per square km) has been rarely attained on the orogens, as (1) few rocks are generally suitable for paleomagnetic investigations, (2) some of them typically lost their original magnetization due to magnetic overprint, and (3) paleomagnetists mostly focused on the regional-scale rotation pattern.

The Maghrebic chain of western Sicily (Figure 1) is a classical case where large-magnitude clockwise (CW) orogenic rotations with respect to the African foreland were already documented some 40 years ago (Schild, 1976), but the available paleomagnetic data resolution is still not high enough to allow discriminating among different tectonic models. In a seminal paper, Channell et al. (1990) showed that rotations decrease stepwise from the internal Panormide tectono-stratigraphic unit (90°–140°) to the Trapanese Unit (47°–70°) and to the most external Saccense Unit of SW Sicily, where no significant rotation was observed (Figure 1b).

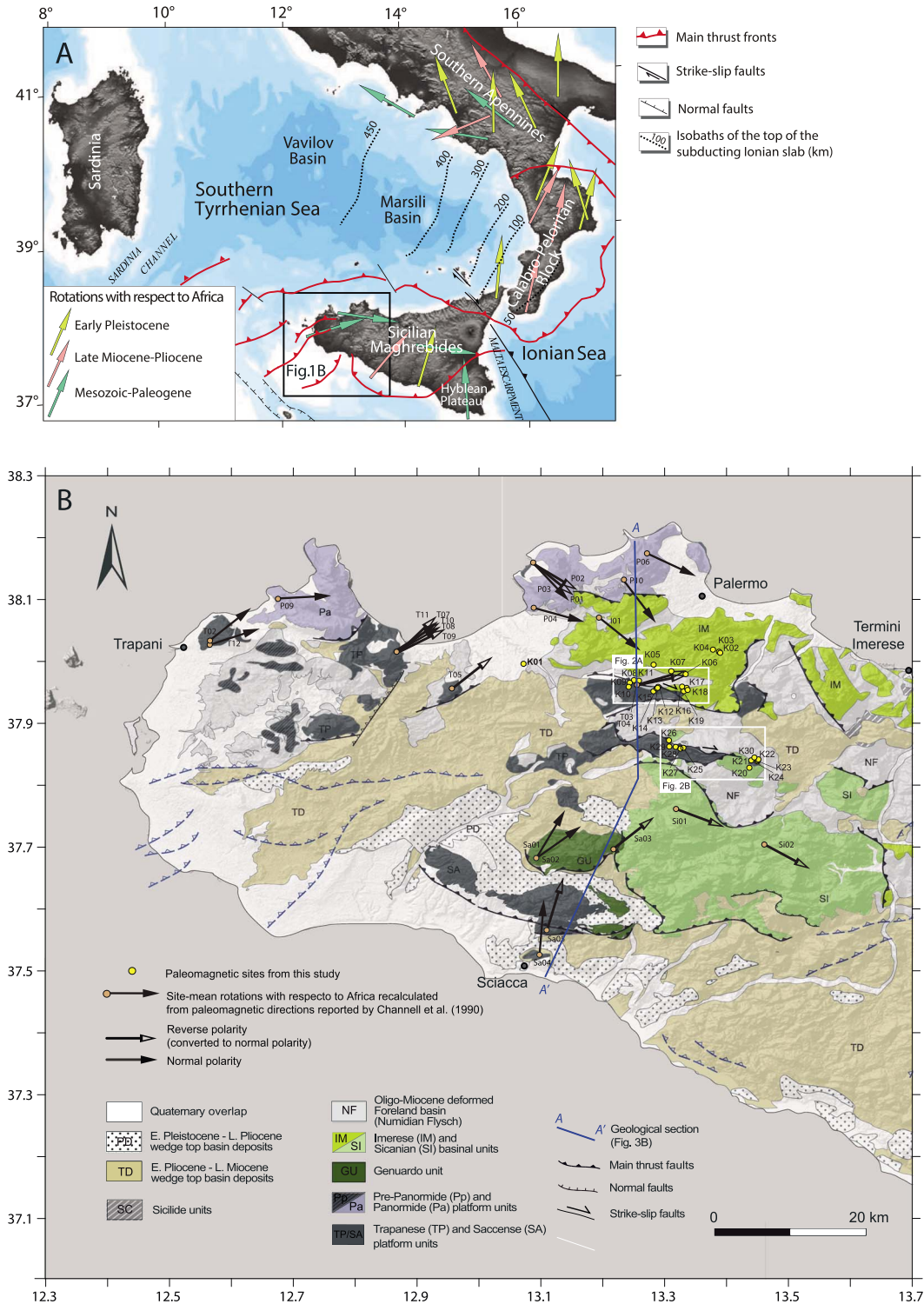


Figure 1. (a) Digital elevation model of the southern Tyrrhenian domain and paleomagnetic rotations with respect to Africa recorded by different age rocks (e.g., Channell et al., 1990; Cifelli et al., 2007; Gattacceca & Speranza, 2002; Maffione et al., 2013; Mattei et al., 2004; Pellegrino et al., 2016; Speranza et al., 2003, 2011). (b) Geological map of western Sicily and previous paleomagnetic rotations from Jurassic-Eocene rocks (see synthesis by Channell et al., 1990) reevaluated considering updated African paleopoles by Torsvik et al. (2012).

Consequently, Channell et al. (1990) and Oldow et al. (1990) proposed that each nappe of western Sicily (corresponding to a given paleogeographic unit) rotated CW during emplacement, carrying (and rotating) the whole overlying nappe stack. Thus, considering a forward orogenic propagation without significant

out-of-sequence thrusting, the measured rotations decrease stepwise from the internal nappes—that underwent multiple rotational episodes—to the external foreland, where no rotation occurs.

More recently, Giunta et al. (2000), Renda et al. (2000), Guarnieri (2004), and Nigro and Renda (2005) suggested that CW rotations of NW Sicily are related to the activity of several late-orogenic WNW-ESE dextral strike-slip faults. The two different rotational models imply great differences in tectonic style. In fact, if rotations were due to rotational nappes rigidly pivoting around a pole located at the western Sicily margin (according to Oldow et al., 1990), southward displacements of ~50 km are expected in central Sicily for each rotating nappe, if 30° individual nappe rotations are assumed. If, on the other hand, the rotations were due to strike-slip tectonics, they should characterize only strike-slip deformation zones hosting rigid blocks rotating about themselves, with no net tectonic displacement.

Thus, paleomagnetism could yield crucial constraints to unravel the tectonic style of the Maghrebian chain of Sicily, as relying on surface geology, shallow wells, seismic reflection data, and palinspastic restoration of geological cross sections, both a tectonic style characterized by several superimposed nappes with shortening exceeding the 50% of initial foreland length (i.e., over 200 km, Catalano et al., 2000, 2013; Finetti et al., 2005; Gasparo Morticelli et al., 2015; Roure et al., 1990), and a thinner wedge with low shortening values not exceeding few tens of kilometers (Butler & Lickorish, 1997; Lickorish et al., 1999) were proposed. At present the two end-member tectonic models cannot be discriminated on the sole basis of paleomagnetic data, as some tectono-stratigraphic units (as the Imerese Unit) were not paleomagnetically investigated, and no ad-hoc paleomagnetic analysis was addressed to the dextral strike-slip faults.

In this paper we report on a detailed paleomagnetic investigation of the Imerese and Trapanese units of the NW Sicily chain. Most of the paleomagnetic sites were gathered across two WNW-ESE ridges (Mt. Kumeta and Rocca Busambra, Figures 1b and 2) bounded to the north by high-angle reverse faults with dextral strike-slip components that probably represent the most clear strike-slip structures of Sicily. The rotation gradients moving away from the faults, the comparison with rotations recorded by adjacent nappes, and the reevaluation of the overall Sicilian paleomagnetic data set allow univocally constraining the tectonic significance of the great CW rotations measured in Sicily.

2. The Maghrebian Chain of Western Sicily: Sedimentary Characteristics and Tectonic Style

The Maghrebian chain of western Sicily developed from a composite paleogeographic setting, consisting of Mesozoic carbonate platforms and adjacent deep-water domains, distributed on an articulated continental margin formerly located along the southern Tethyan realm (Catalano et al., 1996). The different paleogeographic units form individual nappes of the Sicilian orogenic wedge (Figure 1b), so that their position within the nappe pile has been related to their paleogeographic location.

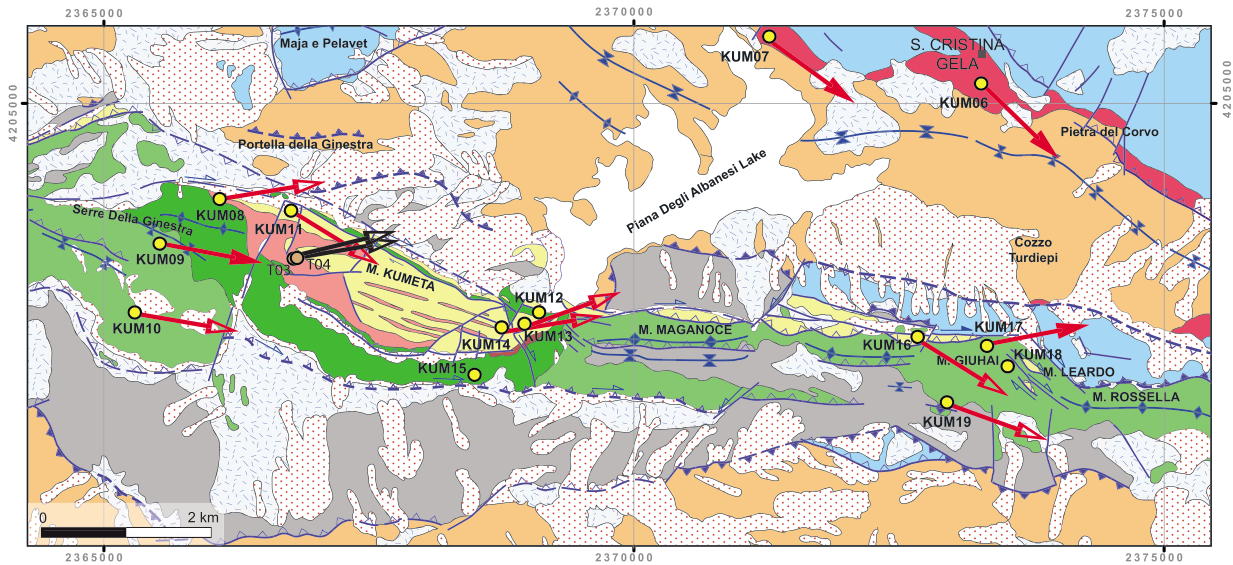
Starting from the higher tectonic unit of the thrust wedge (likely corresponding to the most internal paleogeographic domain), the Sicilide Unit is composed by Cretaceous-Oligocene pelagic shales, marls, and limestones detached from their substratum (Figure 3a).

The 1,500 to 2,300-m-thick Panormide Unit consists of Upper Triassic-lower Oligocene reef to back-reef lagoon limestones, with thin horizons of Jurassic seamount pelagites and Cretaceous-Eocene pelagic calcilutites.

The 800 to 1,400-m-thick mid-Carnian to lower Miocene Imerese slope-to-basin succession is composed by pelagic carbonates and silico-carbonates interbedded with platform-derived detrital carbonates. The Panormide and Imerese units are topped by the 600 to 2,000-m-thick Numidian Flysch Fm., formed by upper Oligocene-lower Miocene siliciclastic foredeep turbidites that are often completely detached from their substratum.

The ~1,400-m-thick Sicanian Unit consists of bedded mid-Triassic-lower Oligocene basinal cherty limestones and marls, passing upward to upper Oligocene-upper Miocene marls and calcarenites. The thick (up to 4,000 m) Trapanese and Saccense Units are very similar, both being made by massive Upper Triassic-Lower Jurassic shallow-water limestones, unconformably followed by middle Jurassic-Eocene pelagic carbonates and marls deposited on seamount morphology, and Burdigalian-lower Tortonian clastic carbonates and outer shelf marls. An extensive system of neptunian dykes can be recognized in the lower Jurassic

A. Monte Kumeta



B. Rocca Busambra

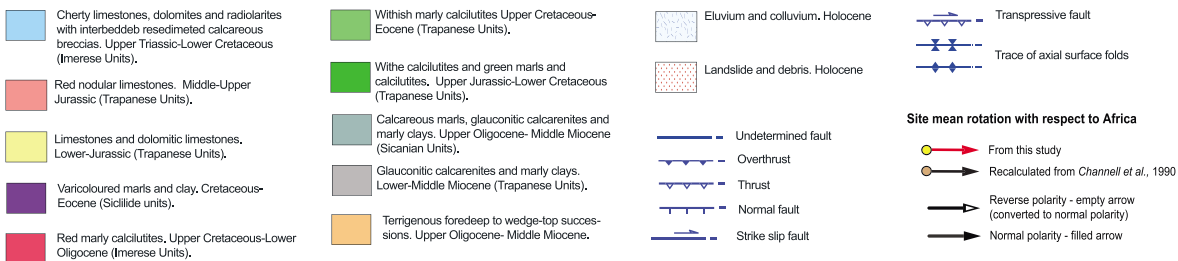
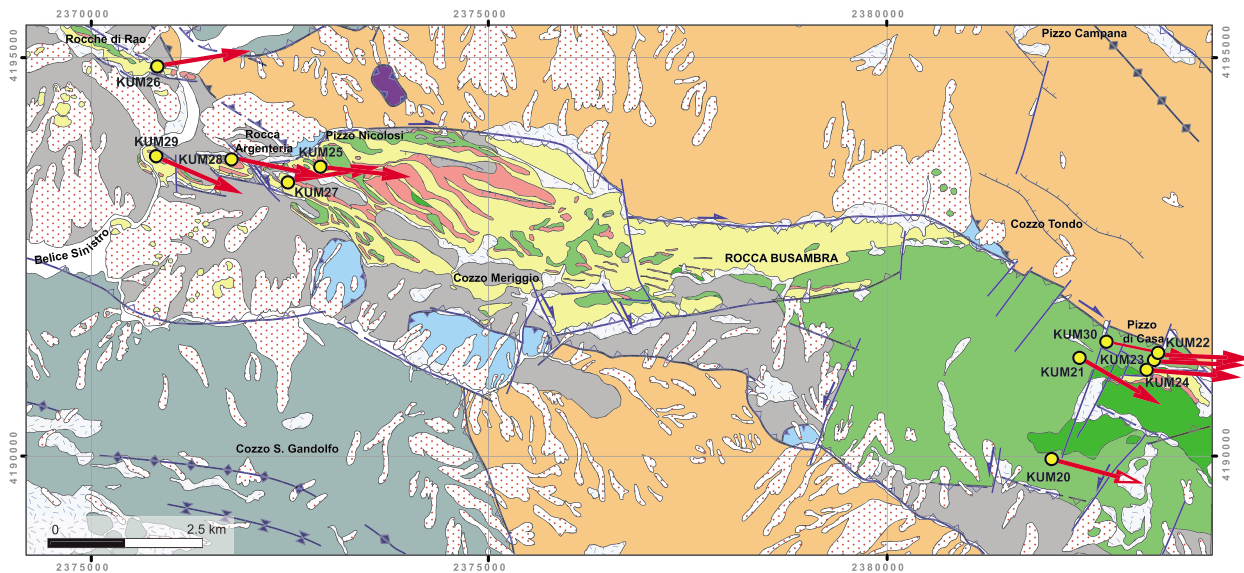


Figure 2. Geological maps of (a) Mt. Kumeta and (b) Rocca Busambra and paleomagnetic rotations from this study, Nairn et al. (1985) (site T04) and Channell et al. (1990) (site T03).

limestones (Inci Fm.) of the Trapanese succession. Both the Sicanian and Trapanese units are unconformably covered by upper Miocene clastic and terrigenous sediments filling syn-tectonic wedge-top basins (Gugliotta et al., 2014).

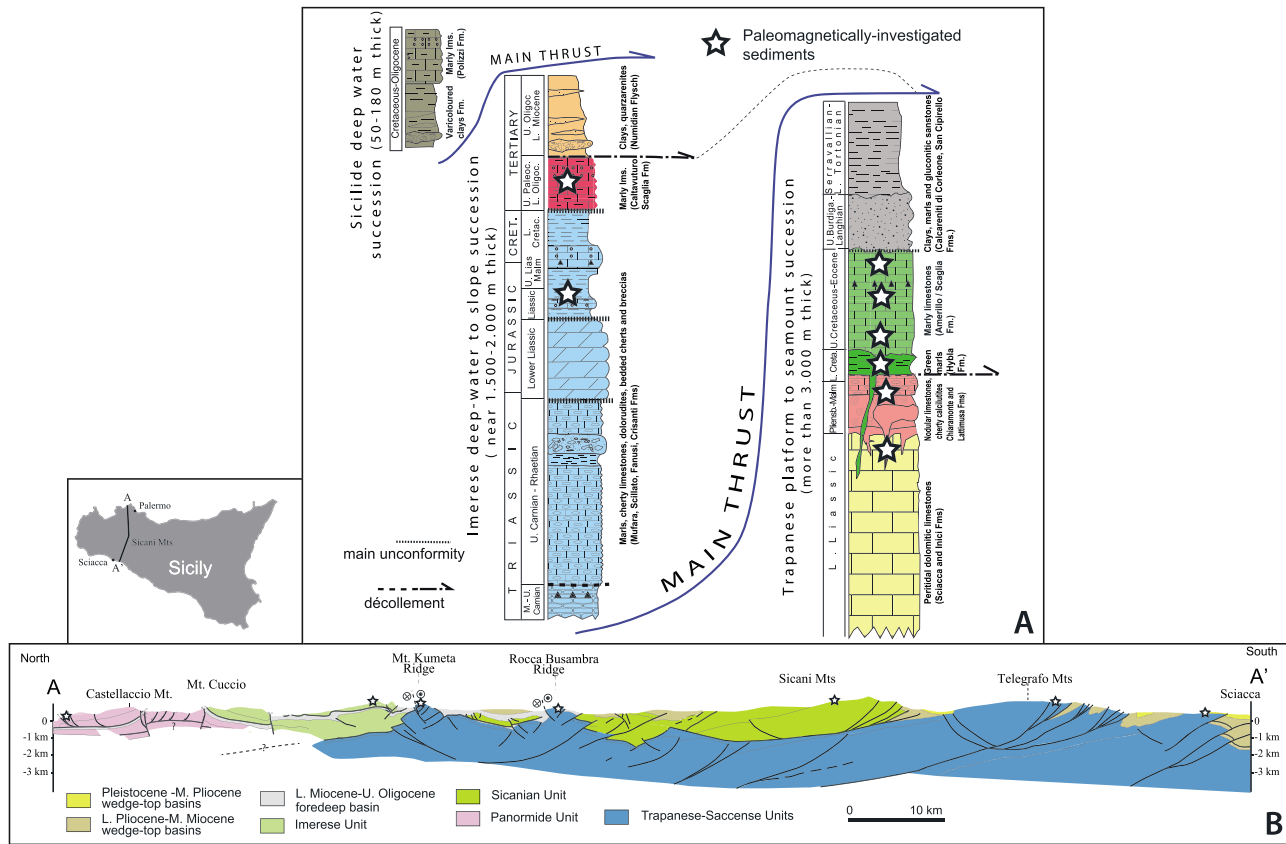


Figure 3. (A) Stratigraphic columns of the Imerese and Trapanese units paleomagnetically investigated in this work. The stars indicate sediments paleomagnetically investigated in this work; (b) geological cross sections of the west Sicily Maghrebides (see also Figure 1b for location). The stars indicate Jurassic-Eocene sediments investigated by Channell et al. (1990) and this work.

The Genuardo Unit is a limited exposure succession (~50 km²) cropping out between the Saccense and Sicanian units (Figure 2b) and deposited in a shelf margin—slope-to-basin sedimentary environment. It is made up by Upper Triassic-Jurassic reef and shelf margin to upper slope limestones, upward followed by Cretaceous-Eocene pelagic calcilutites and bedded cherts and Oligocene-lower Tortonian outer shelf to coastal clays and calcarenites. The paleogeographic position of the Genuardo Unit is debated, from external (originally adjacent to the Saccense Unit, Catalano & D’Argenio, 1990; Channell et al., 1980, 1990) to internal (adjacent to the Sicanian Unit, Catalano et al., 2000).

Crustal seismic data interpretation suggests that the Sicilian chain is formed by a complex orogenic stack—locally more than 15 km thick—made by SSE-verging imbricates (Accaino et al., 2011). Besides the Panormide carbonates, located only in NW Sicily, an ~5-km-thick thrust wedge made of the pelagic Imerese and Sicanian units overrides a >10-km-thick stack of carbonate platform thrusts deriving from the Trapanese and possibly the Saccense units. The exposed sediments, and likely the buried units as well, are completely detached from the crystalline basement (Catalano, Valenti, et al., 2013, and references therein). Upper Miocene to middle Pleistocene wedge-top successions (clastics, pelagites, and evaporites) unconformably seal the underlying tectonic stack (Gugliotta et al., 2014).

Both thin-skinned and thick-skinned thrust tectonics occurred during the buildup of the Sicilian chain (Gasparo Morticelli et al., 2015). During a first Serravallian-middle Tortonian tectonic event, shallow-seated thrusting involved the Imerese and Sicanian basinal units, producing thrust-sheet imbricate-fans and a duplex geometry (Catalano et al., 2000). Afterward, since late Tortonian times, thrusts detached from the buried thick carbonate platform of the Trapanese Unit, forming axial culminations and ramp structures locally offset by high-angle, reverse, and dextral transpressive faults (Avellone et al., 2011; Gugliotta & Gasparo Morticelli, 2012). Fold axes observed in the more internal (Panormide, Imerese, and Sicanian) units are grouped along different trends that are interpreted to arise from the interplay between ongoing late

Miocene compression and vertical axis rotations as documented by paleomagnetism (Avellone et al., 2010; Oldow et al., 1990).

Finally, during late Pliocene-Pleistocene times, both thick-skinned and transpressive tectonics occurred. According to crustal seismic data interpretation (Catalano, Valenti, et al., 2013), the upper part of the crystalline basement was duplicated along a sole thrust merging upward with the frontal sector of the chain. In the upper sector of the orogen, the already formed tectonic wedge was cut by S-dipping dextral transpressive faults developing along back-verging thrust fronts (Gasparo Morticelli et al., 2015). The exposed transpressive faults seem to flatten at depth and merge into the main subhorizontal detachments (Figure 3b). Thus, relying on both seismic reflection data acquired in the 1980s (Roure et al., 1990) and 2000s (Catalano, Valenti, et al., 2013), the western Sicilian Maghrebides conform to a classical fold-and-thrust belt composed by a nappe stack that lacks major strike-slip systems dismembering the chain at a crustal scale.

3. Geological and Structural Setting of the Mt. Kumeta and Rocca Busambra Ridges

The WSW-ENE trending and ~20-km-long carbonatic ridges of Mt. Kumeta (1,233 m above sea level, Figure 2a) and Rocca Busambra (1,613 m above sea level, Figure 2b) are predominantly formed by massive lower Jurassic shelf limestones of the Inici Fm. (Trapanese Unit). Oligo-Miocene terrigenous foredeep sediments (Numidian Flysch) and younger wedge-top clastic and terrigenous deposits extensively crop out in the lowlands located between the ridges.

Integrated field surveys and seismic reflection profiles (Albanese & Sulli, 2012; Avellone et al., 2010; Catalano, Avellone, Basilone, & Sulli, 2010; Catalano, Avellone, Basilone, Gasparo Morticelli, et al., 2010; Gasparo Morticelli et al., 2017) document that the study area corresponds to a thrust pile made up—from top to bottom—by the following tectono-stratigraphic units separated by regional décollements (Figure 3b): (1) a thin (few tens of meters), highly deformed and very discontinuous level of varicolored clays, remnants of the Sicilide nappe; (2) a tightly deformed level, up to 2,000 m thick, formed by deep-water carbonates and siliceous sediments (Imerese and Sicanian units) passing upwards to the Numidian Flysch Fm.; and (3) a continuous, slightly deformed massive rocky body of Trapanese carbonates with an average thickness of about 4,000 m.

The highest units of the tectonic pile (Sicilide, Imerese and Sicanian Units, and Numidian Flysch) are characterized by SW-ward verging thrusts and related minor folds that developed during the first Serravallian-middle Tortonian tectonic event. These units shape, on the whole, an imbricated wedge that overthrusts the Trapanese Unit along a gently north-dipping regional detachment surface.

The deepest tectonic unit, consisting of the Trapanese platform carbonates, is mainly buried. It crops out only along the Mt. Kumeta and Rocca Busambra ridges as a consequence of transpressive tectonics that, since Messinian times, displaced the Trapanese Unit as well as the basal décollement of the Imerese Unit. Secondary décollement surfaces locally also occur along the Mt. Kumeta and Rocca Busambra ridges, mainly between the lower Cretaceous marls of the Hybla Fm. and the underlying more competent carbonates.

The Trapanese succession was also cut by syn-sedimentary (middle Jurassic) WNW-ESE oriented (in present-day coordinates) normal faults and fractures frequently filled by neptunian dykes made by middle Jurassic-upper Cretaceous pelagites. Such features developed during carbonate platform drowning related to southern Tethyan passive margin evolution (Di Stefano et al., 2002; Sulli & Interbartolo, 2016). Some of the Jurassic faults were reactivated as transpressive structures since latest Miocene times (Avellone et al., 2010; Basilone et al., 2010).

The dextral strike-slip faults observed on the northern edges of Mt. Kumeta and Rocca Busambra ridges have been subjected to contrasting interpretations. Ghisetti and Vezzani (1981, 1984) suggested that Mt. Kumeta is the western segment of a major E-W tectonic lineament—the so-called “Kumeta-Alcantara” fault system—crosscutting the whole northern Sicily. Other authors (Finetti et al., 1996; Giunta et al., 2000; Nigro & Renda, 1999; Nigro et al., 2000) also attributed a deep crustal nature to the Kumeta-Alcantara fault system, speculating that it belongs to a major shear zone of the southern Tyrrhenian margin.

On the other hand, seismic data and mesostructural analyses (Avellone et al., 2010; Catalano, Avellone, Basilone, & Sulli, 2010; Catalano, Avellone, Basilone, Gasparo Morticelli, et al., 2010) reveal that both carbonate ridges display an antiformal geometry and are bounded along their northern slopes by high-

angle backthrust faults, merging at depth with a subhorizontal décollement (Figure 3b; Avellone et al., 2010; Albanese & Sulli, 2012). Kinematic indicators suggest the occurrence of high-angle dextral E-W transpressive faults (Avellone et al., 2010; Barreca and Maesano, 2012; Gasparo Morticelli et al., 2017), as well as of a NW-SE dextral and NNE-SSW sinistral conjugate fault system, offsetting faults formed during Serravallian-Tortonian tectonics.

4. Previous Paleomagnetic Evidence From Western Sicily

The Jurassic-Cretaceous basic volcanics and dykes scattered in the sedimentary sequences of NW Sicily were paleomagnetically investigated by Schult (1976), who first documented an $\sim 90^\circ$ CW rotation with respect to the Hyblean Plateau (the foreland of the Sicilian chain, Figure 1a) and Africa. Such data were explained with a rigid rotation of west Sicily, related to the dextral shear along an unidentified fault. Channell et al. (1980) sampled seven sites in the upper Cretaceous “Scaglia” pelagic limestones and marls from the main tectono-stratigraphic units of western Sicily (about one site from each unit). They recognized for the first time that the internal units had undergone greater CW rotations than the external units and related the rotation to the dextral shear exerted by the Calabro-Peloritan block (Figure 1a) on the Sicilian Maghrebides. Catalano et al. (1984) sampled 16 sites in the Jurassic-Cretaceous volcanics from NW Sicily. They mostly found unreliable data, although they first documented a $>90^\circ$ rotation of the Panormide unit and first proposed that the rotational differences between different localities could reflect differential nappe rotations. Nairn et al. (1985) sampled the middle Jurassic Rosso Ammonitico reddish nodular limestones from the Trapanese Unit at three different localities, documenting 60° – 80° CW rotations.

Channell et al. (1990) reevaluated previous paleomagnetic evidence and sampled 20 new sites in the Jurassic Rosso Ammonitico and upper Cretaceous-Eocene Scaglia sediments, mainly from the Panormide and Trapanese Units (Figure 1b). They documented a 90° – 140° and 47° – 70° CW rotation of the Panormide and Trapanese Unit (respectively), a large rotation in the order of 100° (but few data available) of the Imerese and Sicilian Units, and no rotation of the external Saccense Unit (the Genuardo Unit—yielding 36° – 65° rotations—was called “Internal Saccense” Unit). Relying on such data, Channell et al. (1990) and Oldow et al. (1990) proposed the model—very popular since then—of a forward migrating wedge formed by nappes rotating during their emplacement and passively carrying (and rotating) the whole overlying nappe stack. The rotations are post-Eocene in age and likely occurred during the middle Miocene-lower Pleistocene shortening episodes of the Maghrebian chain. More recently, Speranza et al. (1999) detailed the evolution versus age of the rotations by studying the syn-orogenic Plio-Pleistocene deposits of SW Sicily and showed that most of the Genuardo and Sicilian Unit rotations occurred before Pliocene (i.e., 5 Ma) times.

All paleomagnetic literature data from preorogenic Jurassic-Eocene rocks of western Sicily are reported in Figure 1b and Table S1 in the supporting information (see online material). Here rotation and flattening are reevaluated with respect to Africa using updated paleopoles by Torsvik et al. (2012), as paleomagnetic directions from the Hyblean Plateau have been recently confirmed to be consistent with updated African directions (Pellegriano et al., 2016). Considering the units and localities paleomagnetically studied by us, the Imerese Unit was previously investigated at only one locality (Sagana, I01) by Channell et al. (1980), while the Trapanese Unit has been sampled at several sites by all paleomagnetists working in western Sicily. The Rosso Ammonitico Fm. of Mt. Kumeta was studied at two sites (T03, T04) by Nairn et al. (1985) and Channell et al. (1990), while Rocca Busambra has not been paleomagnetically investigated so far.

5. Paleomagnetic Sampling and Methods

We gathered 327 oriented samples (30 sites, Table S2 in the supporting information) in NW Sicily, mainly from the Trapanese Unit exposed at Mt. Kumeta (12 sites, Figure 2a) and Rocca Busambra (11 sites, Figure 2b) and subordinately from the Imerese Unit exposed north of Mt. Kumeta (7 sites, Figures 1b and 2a).

In the Imerese Unit we sampled one site in middle Jurassic crinoid limestones and marls and 6 sites in Eocene Scaglia limestones and reddish marls. At Mt. Kumeta we sampled one site in middle-late Jurassic Rosso Ammonitico nodular limestones, 4 sites in Rosso Ammonitico neptunian dykes infilling lower Jurassic shelf limestones, 2 sites in the Hybla Fm. (Albian-Aptian limestones and gray marls), and 5 sites in the Campanian-Eocene Scaglia Fm. At Rocca Busambra we sampled two sites in nodular limestones and hard grounds of the Rosso Ammonitico Fm., one site in Rosso Ammonitico neptunian dykes, one site in braided

Rosso Ammonitico/Campanian Scaglia dykes, and seven sites in the Albian-Eocene Scaglia Fm. Sampling of Mt. Kumeta and Rocca Busambra was arranged to distribute as much as possible the sites along the ridges and investigate rotations at different distances from the strike-slip faults bounding the ridges to the north. Sites were located along three N-S transects at Mt. Kumeta (Figure 2a) and two transects at Rocca Busambra (Figure 2b). Here one Scaglia site (Kum26) was also sampled in a small subridge located north of the main ridge itself. The ages of Rosso Ammonitico and Hybla sites were inferred from available geological maps (Basilone, 2011; Catalano, Avellone, Basilone, & Sulli, 2010; Catalano, Avellone, Basilone, Gasparo Morticelli, et al., 2010; Catalano, Basilone, et al., 2013), while the age of the Scaglia sites was refined by analyzing the pelagic foraminifer and nanoplankton content on rock thin sections at the Palermo University.

At each site we collected 8 to 34 (11 on average) samples using a petrol-powered portable drill cooled by water and oriented them in situ using a magnetic compass corrected for the local magnetic declination for year 2016 (3°E according to NOAA's National Geophysical Data Center, <http://www.ngdc.noaa.gov/geomag/declination.shtml>) and, when possible, also using a Sun compass.

The oriented cores were cut into standard paleomagnetic specimens at the paleomagnetic laboratory of the Istituto Nazionale di Geofisica e Vulcanologia (Rome, Italy). The natural remanent magnetization of each specimen was measured in a magnetically shielded room using a 2G Enterprises DC-superconducting quantum interference device cryogenic magnetometer. All specimens were thermally demagnetized using a Pyrox shielded oven in 11–15 steps up to a maximum temperature of 680 °C.

Demagnetization data were plotted on orthogonal diagrams (Zijderveld, 1967), and the magnetization components of each specimen were isolated by principal component analysis (Kirschvink, 1980). Site-mean paleomagnetic directions were computed using Fisher (1953) statistics and plotted on equal-angle projections. Site-mean rotation and flattening values with respect to Africa were calculated according to Demarest (1983) using reference paleopoles from Torsvik et al. (2012).

6. Results

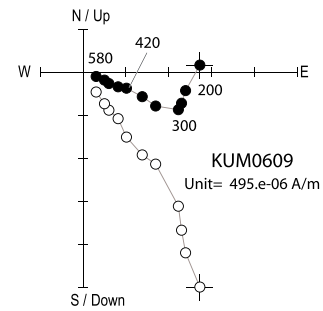
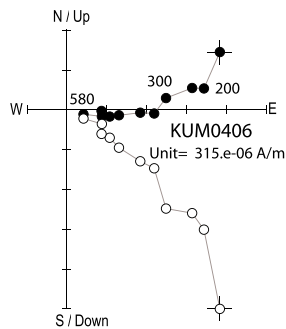
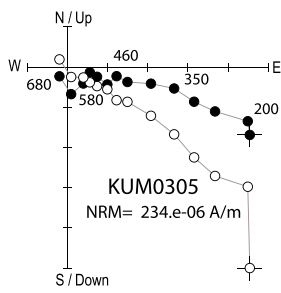
Samples from 4 out of 30 sites (Table S2) were found to be nonmagnetized or yielded erratic demagnetization diagrams and were thus discarded from further considerations. Demagnetization diagrams from the 26 remaining sites show a rather homogeneous magnetic behavior (Figure 4). After the removal of a viscous component at 200 °C, a well-defined characteristic magnetization component (ChRM) was isolated in the 200–600 °C interval for the 30% of the samples, independently from their lithology. In the remaining 70% of the specimens, low-temperature and high-temperature (HT) components were isolated in the 200–400 °C and 320–600 °C temperature intervals, respectively. About 10% of the samples were completely demagnetized at 680 °C, and the 600–680 °C component was found to be subparallel to the ChRM or HT component. The unblocking temperature spectra suggest that the ferromagnetic content is primarily represented by magnetite, and for the 10% of the samples by a mixture of magnetite and hematite. The thermal demagnetization behavior documented by us is at first-order consistent with that reported for the same sediments sampled at different sites by Channell et al. (1980, 1990) and Nairn et al. (1985).

Site-mean directions were calculated by averaging out ChRMs and HT components (Figure 5 and Table S2). Considering the neptunian dikes, the question arises as to whether correct or not their in situ directions for the tilt of the lower Jurassic Inici shelf limestones hosting them. In fact, the Inici Fm. was tilted both during early-middle Jurassic extensional tectonics and late Tertiary shortening of the Maghrebic chain; thus, dike formation could have both pre- and postdated Inici strata tilting. For most of the sites there is field evidence for a Jurassic tilt of the Inici Fm., so that we tilt-corrected only the paleomagnetic direction of site Kum28, where a tilt of the Inici layers due to orogenic shortening was apparent. Our choice is corroborated by the results of site Kum29, sampled in braided neptunian dykes made of both middle-late Jurassic Rosso Ammonitico and Campanian Scaglia reddish limestones. ChRMs from site Kum29 are unrealistically subhorizontal in the tilt-corrected projection, while the in situ plot yields inclinations that are closer to the 30°–40° African values expected in middle-late Jurassic and late Cretaceous times (Figure 6).

Furthermore, to eliminate the bias introduced by mixing Jurassic and late Cretaceous African declinations, the mean direction of site Kum29 was reported to a consistent Jurassic age. To do that, we subtracted the difference (24.0°) between middle-late Jurassic and Campanian expected African declinations to the

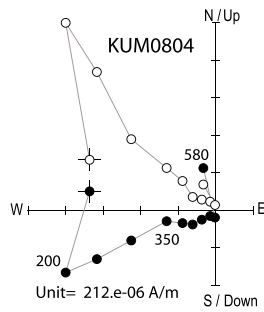
IMERESE UNIT

Caltavuturo (Scaglia) Formation

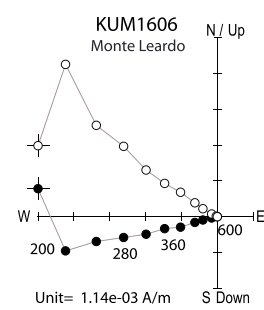
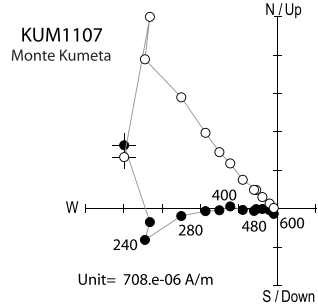


TRAPANESE UNIT - Monte Kumeta

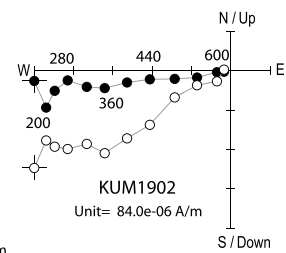
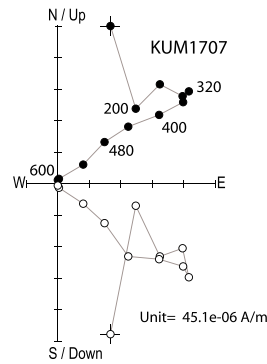
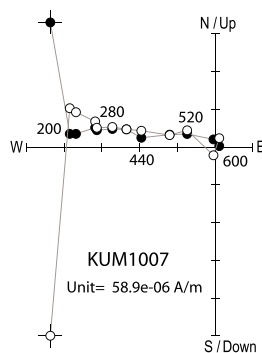
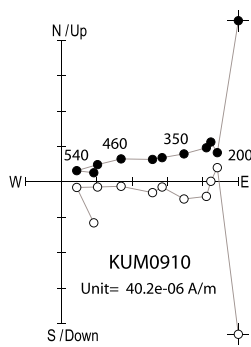
Rosso Ammonitico Formation



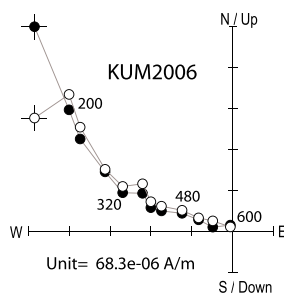
Rosso Ammonitico Formation - Sedimentary dykes



Amerillo (Scaglia) Formation



TRAPANESE UNIT - Rocca Busambra



Amerillo (Scaglia) Formation

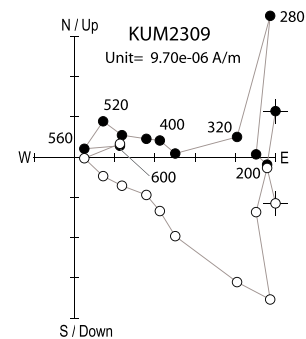
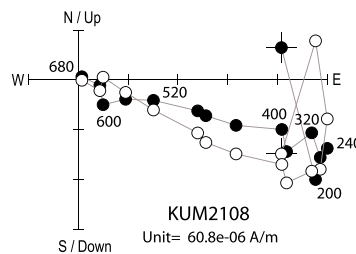


Figure 4. Orthogonal vector diagrams (in situ coordinates) of representative samples carrying typical demagnetization data for each unit and formation. The solid (open) circles represent projection onto the horizontal (vertical) plane. Demagnetization step values are in °C.

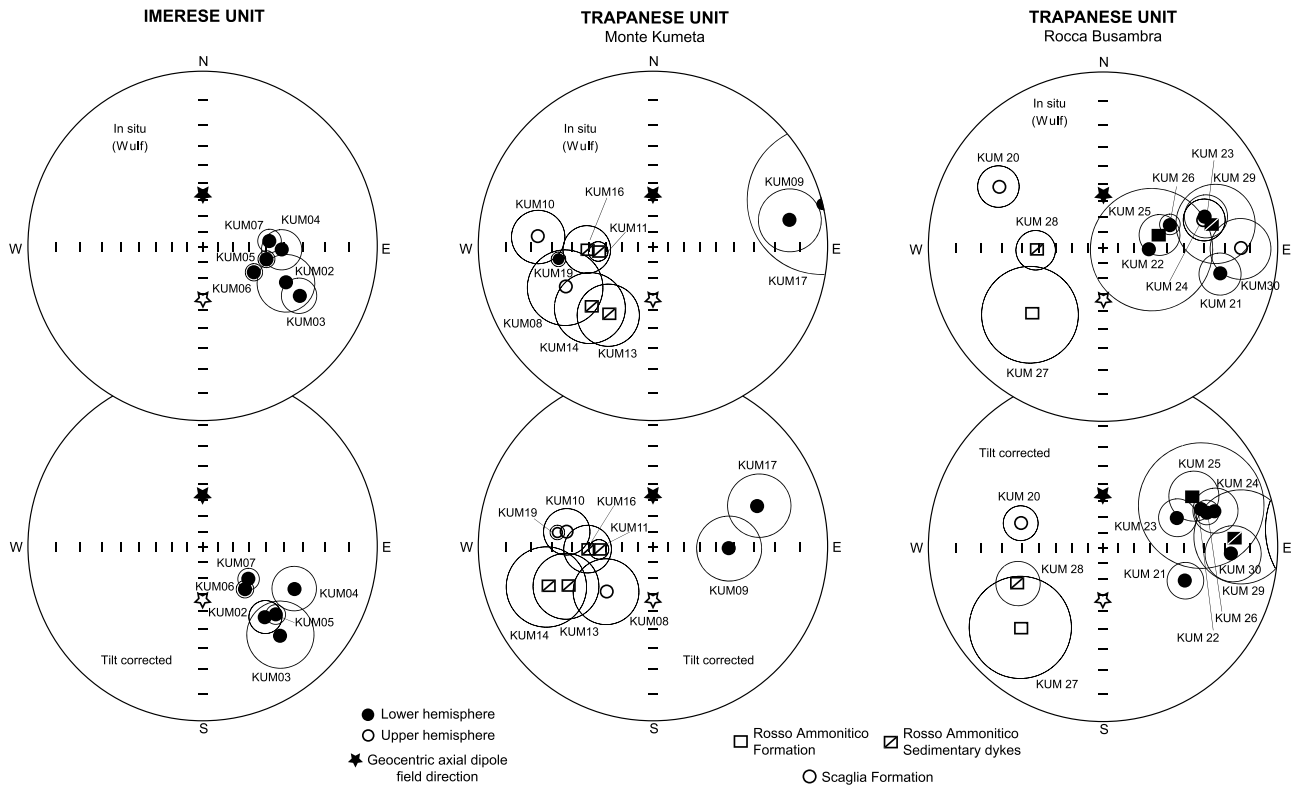


Figure 5. Equal-angle projection of the site-mean paleomagnetic directions gathered in NW Sicily. The solid (open) symbols represent projection onto the lower (upper) hemisphere. The open circles are the projections of the α_{95} cones about the mean directions. The codes correspond to sites shown in Figures 1b and 2 and detailed in Table S2. The solid (empty) star represents the normal (reverse) polarity geocentric axial dipole field direction (normal polarity $D = 0^\circ$; $I = 57^\circ$) expected at the study area.

observed declinations of the Scaglia samples and subsequently calculated the Kum29 site-mean direction (Figure 6).

The α_{95} values relative to the tilt-corrected site-mean paleomagnetic directions vary from 3.7° to 30.0° (12.1° on average, Figure 5 and Table S2). The Eocene Scaglia sites from the Imerese Unit yield uniquely a normal magnetic polarity, while 10 normal and 10 reverse polarity sites are observed in the Trapanese Unit at Mt. Kumeta and Rocca Busambra. The normal polarity of Scaglia sites Kum22–24 is consistent with their Albian biostratigraphic age that falls within the long normal Cretaceous superchron (Gradstein et al., 2012). Eastward (westward) paleomagnetic directions from the normal (reverse) polarity sites are observed. The reversal and fold tests could not be applied on the whole data set, as sites underwent independent rotations (due to both Africa drift and Maghrebian tectonics). The McFadden and McElhinny (1990) reversal test was solely applied on sites Kum27 and Kum30, yielding specimens of dual polarity, and resulted as indeterminate. The mean direction of site Kum27 was calculated considering only six reverse-polarity specimens, as the remaining four normal-polarity samples yielded much smaller paleodeclinations (with respect to both reverse-polarity samples and the neighbor Rosso Ammonitico site Kum25) and were interpreted as being biased by magnetic overprint.

A positive fold test (according to McFadden, 1990) was obtained from HT components of site Kum17, where upper Cretaceous Scaglia layers are folded around a WNW-ESE axis on a metric scale (Figure 7). This result, along with the evidence that paleomagnetic directions are far from the local geocentric axial dipole field direction (Figure 5), support a primary origin of the magnetization. These findings and inferences on magnetization acquisition timing are again in agreement with previous paleomagnetic evidence from Jurassic-Eocene sediments of western Sicily (Channell et al., 1980, 1990; Nairn et al., 1985). Finally, the average of the site-mean flattening values is $2.7^\circ \pm 13.2^\circ$, implying that the paleomagnetic inclinations from western Sicily are consistent with expected African inclinations in the Jurassic-Eocene time window.

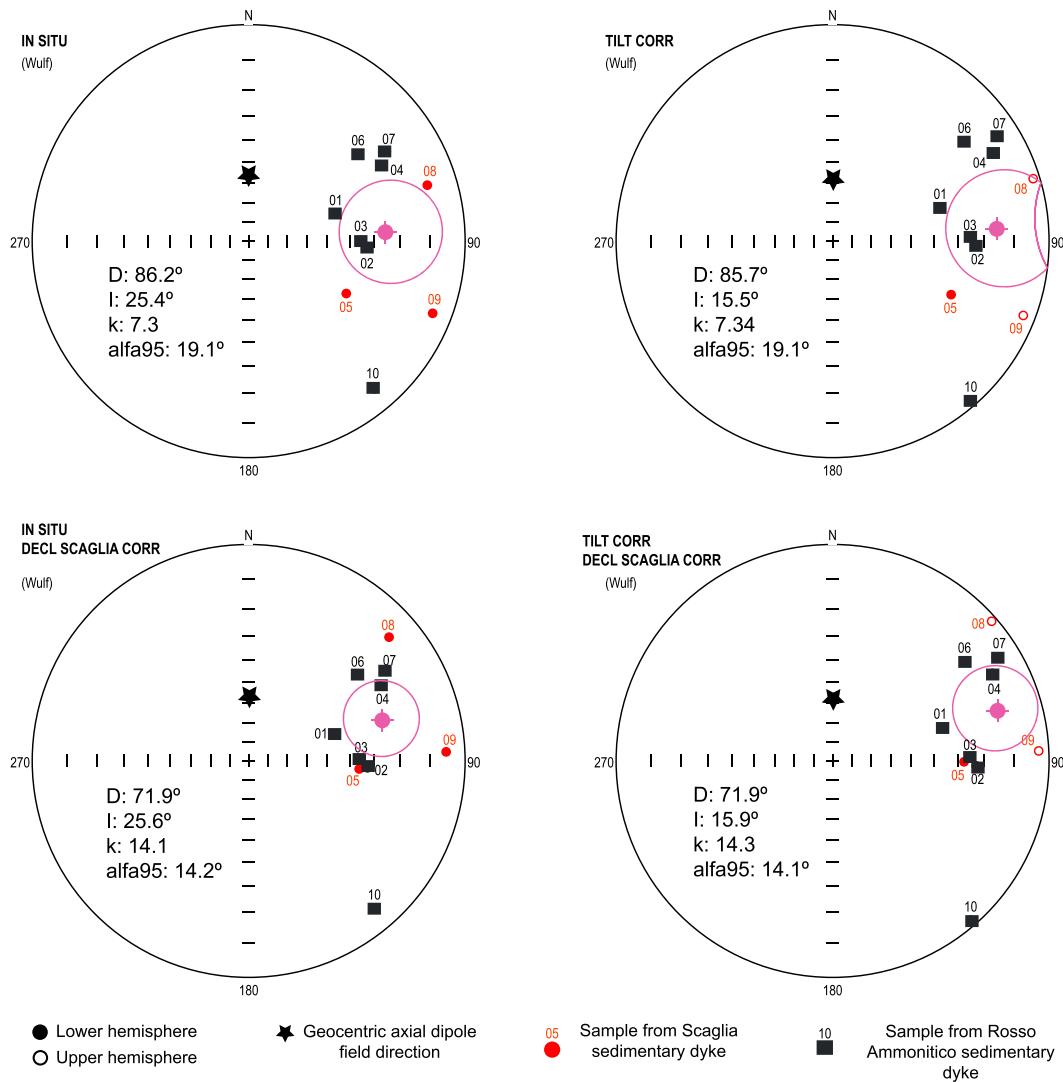


Figure 6. Equal-angle projections of the characteristic directions calculated from specimens of site Kum29 (neptunian dyke made of braided Jurassic Rosso Ammonitico and Campanian Scaglia limestones). The site-mean paleomagnetic directions and the relative α_{95} cones (open circles) are also projected. See text for explanation.

7. Paleomagnetic Rotations With Respect to Africa

Eocene sites from the Imerese Unit yield 114° – 138° CW rotations with respect to Africa (Figure 2a and Table S2), and, together with site I01 by Channell et al. (1980; Figure 1b and Table S1) define an overall $130^{\circ} \pm 8^{\circ}$ rotation. Data from Mt. Kumeta yield variable rotations at different distances from the dextral strike-slip fault bounding the ridge to the north. Rotations of $\sim 120^{\circ}$ characterize sites Kum11 and Kum16 located close to the fault, while six sites located at 200–500 m south of the fault (four by us, one by Nairn et al., 1985, and one by Channell et al., 1990) define consistently a $78^{\circ} \pm 5^{\circ}$ rotation (Figure 8a). Moving further south, rotations rise again to 100° – 110° for three Scaglia sites located at 700 to 1,300-m distance from the fault.

A similar rotation behavior is observed at Rocca Busambra (Figure 8b). Sites Kum28–Kum29—located adjacent to the fault plane—yield a $\sim 110^{\circ}$ rotation, while rotations decrease to $93^{\circ} \pm 8^{\circ}$ considering six sites gathered 200–500 m to the south. Site Kum26, sampled on a small subridge located north of the main Busambra ridge, yields a smaller $82^{\circ} \pm 5^{\circ}$ rotation, possibly due to local tectonics. Moving further south, the rotations of the two Scaglia sites Kum21 and Kum20 rise again to 100° – 120° at 700–2,000 m from the fault.

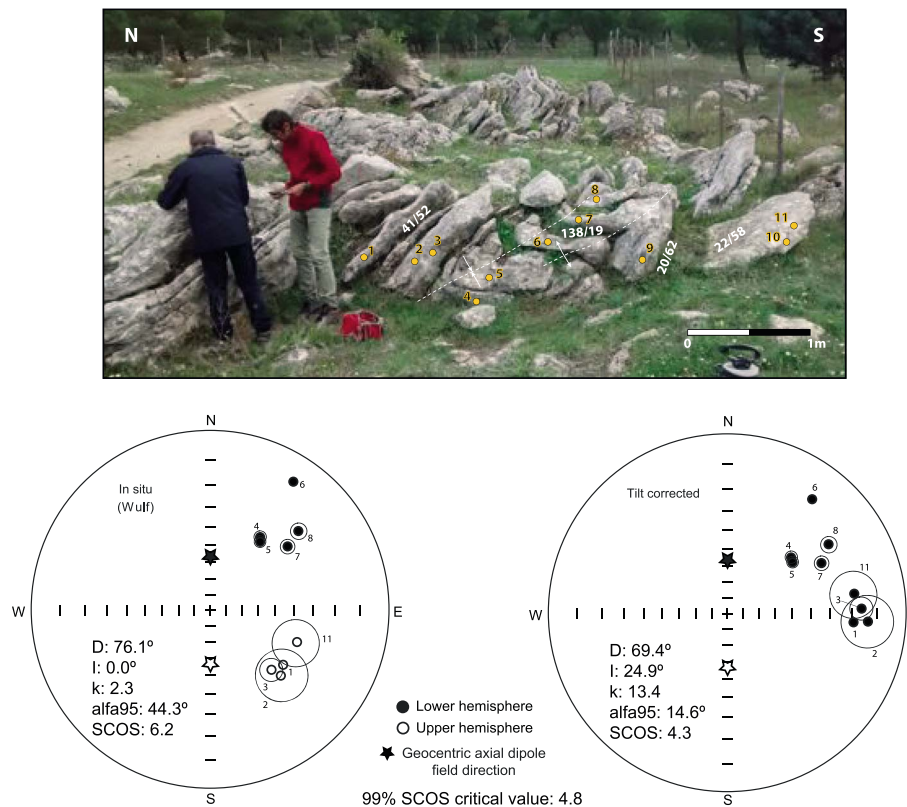


Figure 7. Field picture of site Kum17 (folded Campanian-Maastrichtian Scaglia limestones) and equal-angle projections of the characteristic directions calculated from individual specimens. The yellow circles on picture indicate specimen locations; the numbers indicate bedding (dip azimuth/dip values). Statistical parameters (SCOS values) according to the fold test by McFadden (1990) are detailed.

8. Relevance of Strike-slip Tectonics in Western Sicily

Both at Mt. Kumeta and Rocca Busambra, rotation values are higher (110° – 120°) along the faults, and decrease to 80° – 90° at 200-m south of it (Figures 8a and 8b). Thus, dextral strike-slip shear seems to have induced an excess CW rotation of 20° – 40° that is added to the regional CW rotation of the Trapanese Unit. By assuming a quasi-continuous model for crust deformation (England & McKenzie, 1982; Randall et al., 2011; Sonder et al., 1994), the strike-slip offset can be paleomagnetically evaluated using formulas proposed by Lamb (1987) and Sonder et al. (1994). While the formula by Sonder et al. (1994) requires assumptions on crust rheology, the formula by Lamb (1987)—successfully used in recent works from new Zealand (Randall et al., 2011) and southern Chile (Hernandez-Moreno et al., 2014)—relates simply the strike-slip deformation zone width (W) and fault displacement (D) with the rotation value (θ) of equidimensional blocks smaller than the deformation zone:

$$\theta = 0.5D/W$$

In the case of Mt. Kumeta, by considering a 400-m W value (double of the CW rotated domain south of the fault) and a $\sim 40^{\circ}$ excess rotation (θ) with respect to the regional $\sim 80^{\circ}$ rotation of the Trapanese Unit, we get a total dextral strike-slip offset D of ~ 600 m. This value is similar to maximum strike-slip offsets calculated along transpressive faults crosscutting the Imerese Unit north of Mt. Kumeta (Catalano, Avellone, Basilone, & Sulli, 2010). Considering Rocca Busambra, the smaller excess rotation of $\sim 20^{\circ}$ (along with the same W value) translates into a strike-slip offset of ~ 300 m.

Thus, our data have two main implications on the relevance of strike-slip tectonics in Sicily: First, dextral offsets are small, in the order of few hundreds of meters; second, paleomagnetic rotations due to strike-slip tectonics do not exceed 40° and characterize only narrow land stripes of western Sicily straddling fault themselves, with total widths in the order of 400 m. We conclude that strike-slip tectonics definitely cannot be

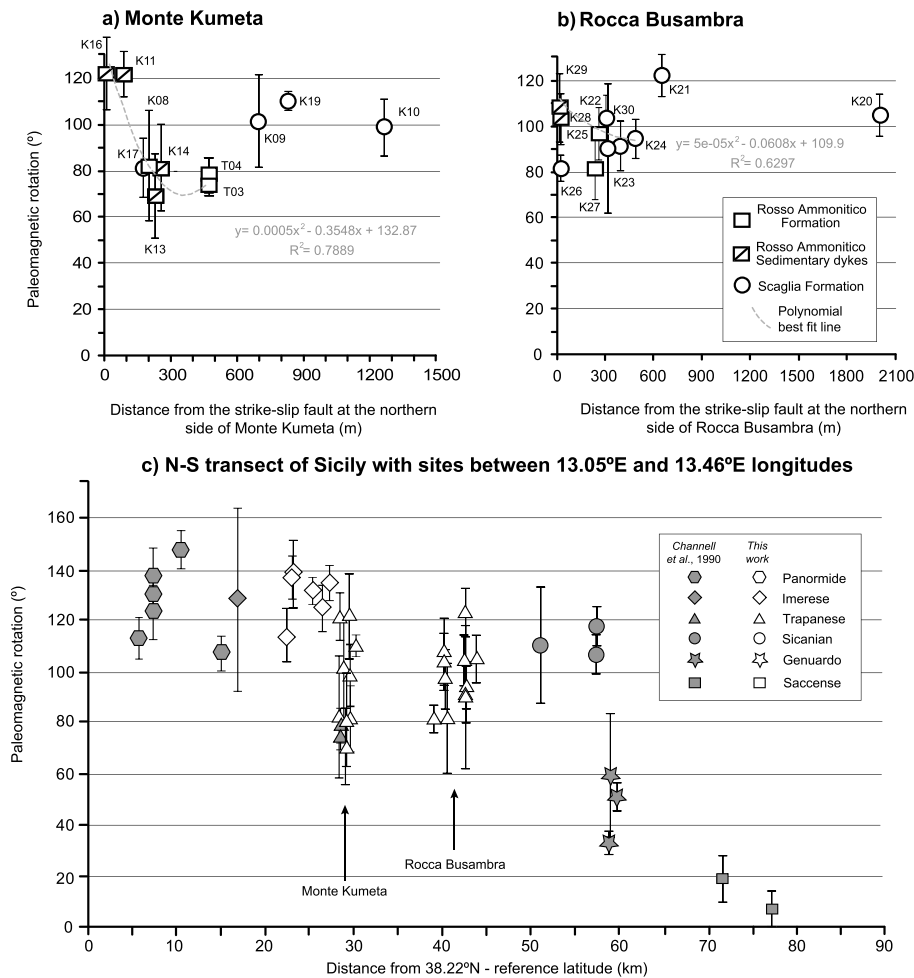


Figure 8. Paleomagnetic rotations (and relative rotation errors) from (a) Mt. Kumeta, (b) Rocca Busambra, and an (c) N-S Sicily transect with sites in the 13.0°–13.5°E longitude range.

responsible of the rotational pattern of western Sicily, where large CW rotations even exceeding 100° characterize the whole internal chain for an area approximating 4,000 km² (Figure 1b).

9. Magnitude and Timing of Rotations in Sicily During Forward Orogenic Propagation

Our data fully corroborate the model put forward by Channell et al. (1990) and Oldow et al. (1990), who suggested that the emplacement of wide internally subcoherent nappes in western Sicily was accompanied by large CW rotations that progressively changed the structural trend of the belt, from an original ~N-S to the present-day ~E-W average structural trend. Thus, the western Sicily chain may be considered the southern limb of a progressive arc (following notation by Cifelli & Mattei, 2010 and Weil et al., 2010), when the overall rotational pattern from the 800-km-long orogenic salient encircling the southern Tyrrhenian Sea is considered (Cifelli et al., 2007; Gattacceca & Speranza, 2002; Maffione et al., 2013; Mattei et al., 2002, 2004; Speranza et al., 2003, 2011, Figure 1a).

The new and reevaluated paleomagnetic data allow further refining the rotational model of west Sicily proposed by Channell et al. (1990) and Oldow et al. (1990). The Imerese Unit, previously characterized by a single site by Channell et al. (1980), is now firmly constrained by seven sites yielding a CW rotation of 130° ± 8° (Figure 8c). The reevaluation of six sites sampled by Channell et al. (1980, 1990) west of Palermo (Figure 1b and Table S1) gives for the Panormide Unit an average rotation of 126° ± 15°. Three Panormide sites from other sectors of the Sicily belt gave smaller 87°–95° rotations and were not considered: site P09 (Custonaci, average of four subsites) was sampled by Schult (1976) in upper Cretaceous volcanics NE of Trapani (Figure 1b), but the

work of Catalano et al. (1984) later showed that Jurassic-Cretaceous volcanics of western Sicily yield mostly unreliable paleomagnetic results; sites P07–P08 (Aculeia, Madonie) were sampled by Channell et al. (1990) in the Madonie Mts. of central Sicily, which likely underwent a different rotational history.

We conclude that there is no differential rotation between the adjacent Panormide and Imerese units exposed west and south of Palermo, as both rotated CW by $\sim 130^\circ$ (Figures 8c). This finding is somehow unexpected, as—relying on data by Channell et al. (1990)—Oldow et al. (1990) proposed that each nappe emplacement in western Sicily yielded an additional CW rotation. The paleogeographic and tectonic relationships between the Panormide and Imerese units are debated, as the Panormide Unit has been classically considered to be more internal and stacked over the Imerese Unit (Catalano & D'Argenio, 1978; Finetti et al., 1996; Roure et al., 1990 among others), although opposite relationships were proposed more recently (Catalano et al., 2000; Catalano, Valenti, et al., 2013). The two units share the same rotation, so that paleomagnetism cannot resolve that controversy. At least two explanations are possible for the Panormide versus Imerese rotational consistency: (1) the Panormide on Imerese (or Imerese on Panormide) tectonic stacking, the oldest middle-late Miocene tectonic episode involving west Sicily carbonates (Catalano, Valenti, et al., 2013), predated CW rotation onset in Sicily; (2) the Panormide and Imerese units are separated by minor thrust fronts and belong to a unique nappe substantially preserving original paleogeographic relationships. This would imply that the \sim E-W contact between the Panormide and Imerese Units observed west of Palermo (Figure 1b) essentially reflects an original shelf-to-basin paleogeographic transition, which should be back-rotated by 130° to be framed in original Tethyan coordinates.

The Scaglia sites exposed in the southern flanks of Mt. Kumeta and Rocca Busambra ridges underwent similar 100° – 120° rotations, while the Inici shelf carbonates forming ridge backbones and their overlapping sediments rotated by only 80° – 90° (Figures 8a and 8b). The same 100° – 120° rotations characterize the Sicanian Unit (Figures 1b and 8c), suggesting that the Scaglia cover of both ridges was décolled from the Trapanese substratum during Sicanian Unit emplacement and rotated further (as already suggested for the Trapanese Unit by Oldow et al., 1990). Alternatively, the Scaglia layers exposed above the Trapanese ridges must be considered to belong to the Sicanian nappe, as already suggested for Rocca Busambra by Agate et al. (1998), Basilone (2009), and Catalano, Avellone, Basilone, Gasparo Morticelli, et al. (2010).

Finally, the rotation values of the Mt. Kumeta and Rocca Busambra shelf limestone backbones are constrained to $78^\circ \pm 5^\circ$ and $93^\circ \pm 8^\circ$, respectively. The reevaluated rotation of the Trapanese Unit west of 13.0° E considering data by Channell et al. (1980, 1990) and Nairn et al. (1985; Table S1) is $67^\circ \pm 21^\circ$, which is higher by about 10° than that proposed by Channell et al. (1990) due to significant differences in the Jurassic African paleopoles used by us and by Channell et al. (1990).

The rotations of Mt. Kumeta and Rocca Busambra are both consistent (considering error bars) with the rotation of the Trapanese Unit west of 13.0° E. However, Rocca Busambra underwent an additional (and statistically significant) $\sim 15^\circ$ CW rotation with respect to Mt. Kumeta, and this is again unexpected considering the model of forward rotational thrust propagation that implies a stepwise decrease of rotation values in the progressively more external nappes (Oldow et al., 1990). However, we note that the average structural trend of Mt. Kumeta and Rocca Busambra is $N96^\circ$ E and $N104^\circ$ E respectively, so that their structural direction difference (8°) is similar to their paleomagnetic rotation difference ($16^\circ \pm 13^\circ$). Thus, we infer that the excess $\sim 15^\circ$ rotation of Rocca Busambra is due to local oroclinal bending effects (e.g., Cifelli & Mattei, 2010) within the Trapanese thrust system.

The overall paleomagnetic data set from western Sicily allows depicting an updated scenario of relative chronology and magnitude of CW nappe rotation occurring since middle-late Miocene times in the 13.0° – 13.5° E chain sector (Figure 9). Similarly to the model by Oldow et al. (1990) and according to available geological evidence (Catalano, Valenti, et al., 2013), we infer that forward orogenic propagation occurred and that during emplacement each nappe rotated passively the whole overlying orogenic stack. Consequently, the unit located on top of the orogenic pile recorded the sum of all individual nappe rotations. During a first late Serravallian-early Tortonian rotation episode, the Panormide and Imerese units—likely pertaining to adjacent paleogeographic locations—overthrust the Sicanian basin and rotated by 20° . Afterward, the Sicanian Unit (including the detached Scaglia sediments overlying Mt. Kumeta and Rocca Busambra) thrust over the Trapanese Unit by rotating 30° . Considering data from Mt. Kumeta, we assign to the Trapanese Unit an average 80° rotation.

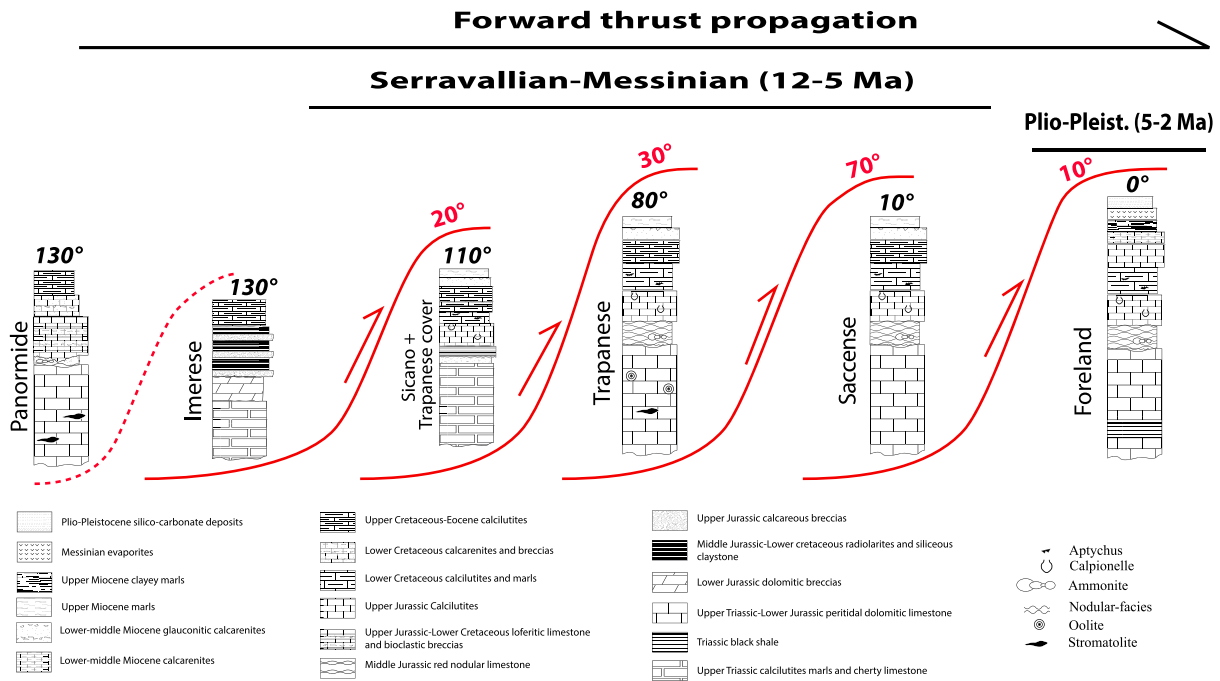


Figure 9. Interpretative model of rotations introduced by nappe emplacement in western Sicily within the 13.0°–13.5°E longitude range. The small extent Genuardo Unit is omitted (see text). The black numbers indicate the rotation values measured in each tectono-stratigraphic unit. The red numbers indicate the inferred rotations yielded by the individual nappe emplacements during the middle-late Miocene to early Pleistocene forward thrust propagation process. Unit thicknesses are not in scale.

The evolution of the Genuardo Unit is questionable. One possible scenario is that, since late Tortonian times, the Trapanese Unit rotated by 30° while tectonically overriding the Genuardo Unit that in turn thrust on top of the Saccense Unit with a rotation of 40° occurring before the deposition of lower Pliocene Trubi chalks (i.e., before 5 Ma), sealing the Genuardo-Saccense tectonic contact. The reliability of this scenario is weakened by two bits of evidence: (1) The Genuardo Unit has a very limited extension; it crops out for only 50 km² and was not recovered by wells below other adjacent units; thus, it is hard to imagine that such a small rock body carried on top of it and rotated the whole Maghrebien orogen of central Sicily extending for some 2,500 km² (Figure 2b) and (2) a more internal location (adjacent to the Sicilian Unit) was recently inferred on structural grounds by Catalano et al. (2000). Thus, although three paleomagnetic rotation values (Figure 8c) suggest for the Genuardo Unit an external paleogeographic position (i.e., between the Trapanese and Saccense units), more geological, structural, and paleomagnetic data are needed to constrain its rotational evolution. In any case, if the Genuardo Unit is disregarded, the Trapanese Unit thrust over the Saccense Unit inducing a huge 70° rotation that is suggestive of widespread tectonic duplication during the late Tortonian tectonic episode.

The reevaluation of two sites by Channell et al. (1980, 1990) from the Saccense Unit yields a significant average rotation of 12° ± 8°, implying that the latter cannot be considered as autochthonous and underwent a small thrusting-related rotation of ~10° over the foreland. This is consistent with conclusions by Monaco et al. (1996), who considered the Saccense ridges sampled by Channell et al. (1980, 1990) as thrust anticlines. As three 1.73 to 1.95-Ma sites by Speranza et al. (1999) from the Saccense Unit did not yield significant rotations, we conclude that the final Saccense 10° rotation occurred during Pliocene times and was completed before early Pleistocene (Calabrian) times.

Such rotation model is consistent at first approximation with paleomagnetic data from early Pliocene Trubi chalks exposed in the Madonie Mts. of north-central Sicily (Grasso et al., 1987), documenting ~20° CW rotations, besides a magnetic overprint. Such data would confirm both our rotation chronology (most of the large rotations documented in Jurassic-Eocene rocks occurred before Pliocene) and mechanism (rotations are driven by outer nappe emplacement passively carrying and rotating the whole orogen). However, it must be acknowledged that it is not clear if (and to what extent) the rotations documented by Grasso et al. (1987) are related to local strike-slip tectonics. It is also difficult to assess the chronological

implications of the 10° – 30° CW rotations measured in Plio-Pleistocene sediments from the “Gela Nappe” of central-southern Sicily (Duermeijer & Langereis, 1998; Scheepers & Langereis, 1993), as no local Mesozoic-lower Tertiary paleomagnetic data can be used for a comparison. Speranza et al. (2003)—relying on data from SE Sicily—suggested that most of the rotation of the Gela Nappe is older than Tortonian times, but such conclusion is weakened by the possible magnetic overprint of the Tortonian sites from the Terravecchia Fm.

To sum up, we reconstruct for the west Sicily chain four main thrust events that yielded each a 10° – 70° CW rotation, passively carrying and rotating the whole overlying nappe stack. It is worth noting that individual nappe rotations seem to have increased during the orogenic process, if the final stacking of the Saccense Unit over the foreland is not considered. The first middle-late Miocene (minor?) shortening episodes affecting the Panormide and Imerese units did not yield rotations, while rotations occurring during the subsequent late Miocene nappe emplacement episodes increased from 20° to 70° . By assuming that rotations started at ~ 12 Ma (late Serravallian age of the Imerese on Sicilian stacking according to Catalano, Valenti, et al., 2013) and ended in the Saccense Unit at ~ 2 Ma (considering paleomagnetic data by Speranza et al., 1999), we get an average 13° /Myr rotation rate. However, if the final 10° Saccense rotation is excluded, the Trapanese Unit thrust over the Saccense Unit before 5 Ma, translating to a higher 17° /Myr rate that is a realistic value considering rates measured for rotating nappes (e.g., Mattei et al., 2004).

The progressive rise of individual nappe rotation during the thrust propagation process translates to progressive increase of shortening produced by individual nappe emplacement, if rigid rotations and the same rotation pole are assumed. A rigid rotation in the 13.0° – 13.5° E longitude sector is supported by the consistency of rotations yielded by far sites sampled in the same unit (Figures 1b and 2). The rotations west of 13.0° E are less well constrained, but data from the Trapanese Unit are indeed consistent with a rigid rotation of the whole western Sicily.

By considering a rotation pole located at the western Sicily coast, CW rotations of 10° – 70° imply individual nappe shortening values in the order of 20–120 km at the 13.5° E longitude. In Figure 10 we show a paleogeographic reconstruction at 23 Ma (Oligo-Miocene boundary, before Corsica-Sardinia rotation, e.g., Gattacceca et al., 2007) that incorporates both geologic and paleomagnetic evidence from the central Mediterranean domain. The individual Sicilian nappes are back-rotated according to the whole paleomagnetic evidence of Figure 8c, by assuming a rotation pole located along the west Sicily coast. In such reconstruction, the Imerese and Sicilian units represent two sunken steps of the Panormide and Trapanese shelf carbonate units (respectively), eventually leading to the deep oceanic floor of the Paleo-Ionian Sea. The great 130° CW rotation of the internal Sicilian chain implies that the Panormide Unit—that today seems to be the more internal nappe with respect to the Hyblean-African foreland (Figure 1)—was in fact directly connected to the Tunisia shelf of northern Africa. The average trend of fold axes and thrust directions observed at present in the Panormide-Imerese and Trapanese units is $N320^{\circ}$ and E-W (respectively), implying that back rotated by 130° and 80° (according to paleomagnetism) they get a subparallel trend of $N10^{\circ}$ (Figure 10), which must be considered the pristine tectonic trend at the beginning of orogenic deformation. The high angle occurring between the Panormide-to-Imerese paleo-margin ($N320^{\circ}$) and the pristine fold-thrust directions ($N10^{\circ}$) implies that the Panormide-Imerese paleogeographic boundary was transversal to orogenic front propagation and that it was later incorporated (and rotated) within the chain with limited modification of the original relationship. Our paleogeographic scenario could shed new light on the Panormide-Imerese contact now exposed just W of Palermo (Figure 1) that could be further investigated to understand how the transition from the peri-African shelf carbonates to the deep and oceanic Ionian Sea occurred in Mesozoic times. The pre-rotation pattern of Figure 10 also proves that reconstructing the paleogeography of orogenic arcs without the aid of paleomagnetism leads to unavoidable mistakes.

Overall, the 130° rotation of the Panormide-Imerese units translates to a 230-km total displacement of the chain that is at first approximation consistent with that recently estimated by the interpretation of deep seismic reflection profiles from the central Sicily crustal transect (Gasparo Morticelli et al., 2015). Moreover, this has to be considered a lower bound value, as part of the shortening in the Sicilian chain might have occurred without a rotational component. The average paleomagnetically calculated shortening rate (considering again a 12 to 5-Ma time window and disregarding the Saccense Unit) is in the order of 3 cm/yr that is again consistent with estimates by Gasparo Morticelli et al. (2015).

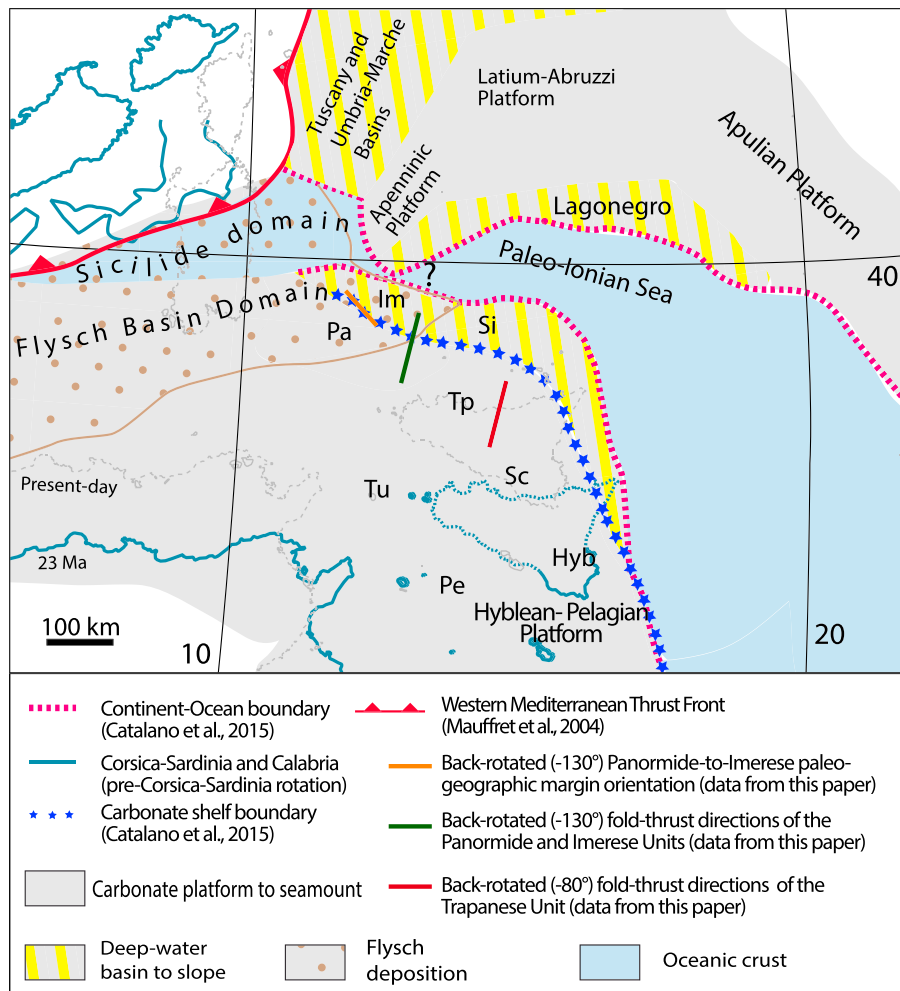


Figure 10. Paleogeographic reconstruction of the central Mediterranean domain at 23 Ma (Oligo-Miocene boundary). Back-rotated paleogeographic and tectonic trends of the Sicilian units are inferred considering paleomagnetic data from this work. Back-rotated trends of the Corsica-Sardinia microplate and the Apenninic platform are after Gattacceca et al. (2007) and Gattacceca and Speranza (2002), respectively. Paleogeographic unit abbreviation: Pa Panormide, Im Imerese, Si Sicilian, Tp Trapanese, Tu Tunisia, Sc Sciacca, Pe Pelagian, Hyb Hyblean. See Catalano et al. (2015) for further details on the shelf and basin paleogeographic distribution.

The Maghrebian chain of Sicily represents the southern limb of the great orogenic salient encircling the southern Tyrrhenian Sea (Figure 1a). Basin spreading and chain shortening occurred synchronously as the result of the passive subduction and SE-ward retreat of the Ionian oceanic slab (Malinverno & Ryan, 1986; Patacca et al., 1990). Rifting of the Tyrrhenian Sea occurred in Serravallian-Messinian times, while oceanic breakup and the formation of the Vavilov and Marsili oceanic basins (Figure 1a) took place during early Pliocene-early Pleistocene times (Kastens et al., 1988; Mattei et al., 2002; Sartori, 2004). The average spreading velocity is 6 cm/yr (Patacca et al., 1990), although pulses up to 19 cm/yr were documented for the early Pleistocene oceanic spreading (Nicolosi et al., 2006).

Paleomagnetic data from western Sicily, coupled with crust setting interpretations (Catalano, Valenti, et al., 2013), show that late Miocene rifting in the Tyrrhenian Sea was accompanied by the emplacement of a thin-skinned high-allochthony orogenic wedge undergoing $>100^\circ$ CW rotations, while the Plio-Pleistocene oceanic breakup and rapid spreading episodes yielded only 10° rotations and the formation of crustal ramps possibly cutting the crystalline basement. Such paleomagnetic-tectonic scenario is mirrored by the southern Apennines, where a thin-skinned high-shortening (>200 km) orogenic wedge rotated counterclockwise by 60° – 100° in late Miocene times (the back-rotated setting of the Apenninic platform is shown in Figure 10), while during Plio-Pleistocene a 20° rotation was associated to the formation of crustal ramps cutting the Apulian carbonates and possibly the basement (Gattacceca & Speranza, 2002; Menardi Noguera & Rea,

2000; Maffione et al., 2013). Thus, chronology and magnitude of paleomagnetic rotations from Sicily and the southern Apennines represent pivotal data to understand the kinematics and dynamics of southern Tyrrhenian Sea spreading and southern Apennines-Calabria-Sicilian Maghrebides orogenic salient formation. Large ($>100^\circ$) rotations are proxy for large displacements and probably can occur only in wedges bounded by subhorizontal décollement faults and detached from crystalline basement.

Sicily represents the easternmost part of the Maghreb chain developing along NW Africa margin. Previous studies along the Algerian Maghrebides documented again CW rotation occurrence (Derder et al., 2011, 2013), although crustal setting, rotation age (post-Mio-Pliocene), and rotating domain size (<1 km) suggested a block-rotation model driven by dextral strike-slip tectonics. Thus, it seems that an eastward tectonic change occurs in the Maghreb chain of northern Africa, from Algeria—where strike-slip tectonics and block rotation occur—to Sicily, where CW rotations are conversely the result of rotational nappe emplacement along the great peri-Tyrrhenian orogenic salient. Strike-slip-driven CW rotations of Algeria are consistent with local tectonic and seismo-tectonic evidence, showing that the Africa-Europe oblique convergence is partitioned in NE-trending thrust faults and E-W dextral strike-slip faults (Meghraoui et al., 1988).

10. Conclusions

New paleomagnetic data gathered from Mt. Kumeta and Rocca Busambra, two WNW-ESE ridges from the Trapanese Unit bounded to the north by dextral strike-slip faults, show that fault drag yielded 20° – 40° CW rotations at fault planes that are annulled to the regional rotation backgrounds of the Trapanese Unit at only 200 m to the south. Such values translate to paleomagnetically calculated strike-slip offsets do not exceeding 600 and 300 m (respectively) and show that strike-slip tectonics yielded in Sicily CW rotations only along narrow land stripes of ~ 400 -m width straddling faults themselves. Thus, our data demonstrate that strike-slip tectonics did not play a significant role in the genesis of the widespread and large CW rotations measured in western Sicily. The new data fully confirm the model by Channell et al. (1990) and Oldow et al. (1990), suggesting that large and internally coherent nappes rotated CW during their emplacement, and underwent additional rotations on top of outer nappes formed during forward orogenic propagation.

New data gathered in the Imerese Unit—along with the reevaluation of the preexisting paleomagnetic data set with updated African paleopoles—allow refining the rotation value characterizing each tectono-stratigraphic unit of western Sicily in the 13.0° – 13.5° E longitude range. No differential rotation occurred between the Panormide and Imerese units, both characterized by 130° rotation values and likely representing contiguous paleogeographic domains separated by secondary thrust faults. Considering data from Mt. Kumeta, we constrain at 80° the rotation of the Trapanese Unit, while Rocca Busambra underwent an additional 15° rotation due to local oroclinal bending. The upper Cretaceous-Eocene Scaglia cover of both Mt. Kumeta and Rocca Busambra records an additional 20° – 30° rotation with respect to the Jurassic ridge backbones, implying that it was décolled from the substratum, or it belongs in fact to the similarly rotated Sicanian Unit.

The 130° total rotation of the Panormide-Imerese complex on top of the orogenic pile was attained through late Miocene rotation-thrusting events that increased along time and space, from 20° (thrusting of the Panormide-Imerese complex over the Sicanian basin) to 70° (stacking of the Trapanese onto the Saccense Unit, later rotating by further 10° in Pliocene-lower Pleistocene times). Assuming rigid nappe rotations and a rotation pole along the west Sicily coast, we derive (at a 13.5° E longitude) a total 230-km rotational shortening of the chain and individual nappe displacements in the 20 to 120-km range, although further nonrotational shortening might have occurred. Thus, paleomagnetism definitely represents a proof for the high allochthony of the Maghreb chain of Sicily, consistently with recent seismic reflection data interpretations (Catalano, Valenti, et al., 2013). By further assuming that rotations occurred during late Miocene thrusting events in the 12 to 5-Ma age window (except the Saccense Unit, later stacked onto the foreland), we derive an average $17^\circ/\text{Myr}$ rotation rate, and a paleomagnetically calculated average shortening rate of 3 cm/yr, that is again consistent with recent geological estimates.

Paleomagnetic data from Sicily and the southern Apennines prove that late Miocene rifting in the Tyrrhenian Sea were associated to the formation of thin-skinned high-allochthony (>200 km) wedges undergoing large

(>100°) and opposite sign rotations, while Plio-Pleistocene oceanic breakup was reflected by the formation of crustal ramps with small (10°–20°) additional rotations.

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