40 Ar/ 39 Ar dating and paleomagnetism of the Miocene volcanic succession of Monte Furru (Western Sardinia): Implications for the rotation history of the Corsica-Sardinia Microplate

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$^{40}Ar/^{39}Ar$ dating and paleomagnetism of the Miocene volcanic succession of Monte Furru (western Sardinia): Implications for the rotation history of the Corsica-Sardinia microplate

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Abstract. Although it is widely acknowledged that the Corsica-Sardinia microplate rotated counterclockwise with respect to Europe during Oligocene-Miocene time, the precise timing of this event has yet to be determined. We have measured the age and degree of rotation of a single 'tie-point' in the rotation history of the microplate. Biotite and sanidine $^{40}Ar/^{39}Ar$ age determinations of the 200m-thick Monte Furru volcanic succession indicates that most of the volcanic pile accumulated within less than 200 ky. The paleomagnetic pole obtained for the 12 volcanic flow units comprising this succession indicates that by 18.2 Ma Sardinia remained 13° shy of its final rotation angle. These results demonstrate that the movement of the Corsica-Sardinia block and the opening of the liguro-provençal basin terminated later than previously estimated based on paleomagnetic and geochronologic studies of Sardinian volcanic rocks, in agreement with paleomagnetic data from Sardinian sediments.

Introduction

Accompanying the opening of the liguro-provençal basin, the Corsica-Sardinia microplate drifted eastwards to its current position during Oligo-Miocene, based on various palinspastic reconstructions for this part of the Mediterranean (e.g. [*Mauffret et al.*, 1995]). However, the timing of this event (initiation, rate of rotation, and cessation) remains uncertain.

Paleomagnetic investigations of Sardinian volcanic rocks document a NW to N shift in declination, interpreted as evidence of rotation of a rigid Corsica-Sardinia microplate. By analyzing paleomagnetic and K/Ar geochronologic data from these rocks, *Montigny et al.* [1981] concluded that the 30° rotation of Sardinia-Corsica occurred in the Lower Burdigalian, between 21 and 19.5 Ma (ages re-calculated with decay constants from *Steiger and Jäger* [1977]). However, statistical evaluation of the pre-existing paleomagnetic and geochronological data on volcanic rocks by *Todesco and Vigliotti* [1993] and *Speranza* [1999] showed while the onset of rotation could be constrained to ~21.5 Ma, termination could not be accurately assessed primarily due to uncertainties introduced by secular variation. *Vigliotti and Kent* [1990] and *Vigliotti and Langenheim* [1995] investigated Miocene sedimentary rocks from Corsica and Sardinia respectively. Results from Corsica were not deemed reliable, but those from Sardinia indicated that rotation was incomplete prior to 15 Ma. *Speranza et al.* [1999] investigated Miocene sedimentary rocks from Sardinian, and documented a 20° rotation of Sardinia subsequent to 18.4 Ma. Thus there exists a discrepancy in the timing of cessation of rotation as inferred from studies of volcanic and sedimentary rocks.

Paleomagnetic analyses of 16 sites spanning the Miocene eruptive succession of Monte Furru demonstrated an apparently gradual clockwise rotation of declination from 290°-340° at the base to 350°-015° at the top [*Assorgia et al.*, 1994]. These paleomagnetic data were interpreted as possible evidence for the counterclockwise rotation of Sardinia. Subsequently, we have acquired $^{40}Ar/^{39}Ar$ ages and new paleomagnetic data for most of the units comprising the Monte Furru, in a well understood stratigraphic setting, to help constrain the timing of the tectonic rotation of Sardinia.

Geological setting

~1000 m of volcanic rocks of upper Oligocene to lower Miocene are exposed near Bosa on the west-central coast of Sardinia. This succession is composed of basaltic to andesitic lava flows, domes, and interbedded pyroclastic breccias, and of intermediate to rhyolitic, predominately pyroclastic volcanic products including flow, fall and surge deposits. The uppermost 200 m of the volcanic succession is well exposed at Monte Furru (40°17'N, 8°30'E), where the following stratigraphy has been established, from base to top: a) the Great Ignimbrite of Bosa (GIB), a rhyodacitic (Qtz+Pl+Bt±Kfs±Hbl) ignimbrite, composed of three flow units (designated BO1, BO2, BO3) attaining a total maximum thickness of 100 m, b) a rhyodacitic to dacitic (Pl+Cpx+Bt±Hbl±Qtz) composite ignimbrite ~70 m thick (four flows, MF1-4), c) a 20 m thick ignimbrite comprised of two flow units (IF1, IF2), and finally d) a 15 m thick dacitic (Pl+Bt+Cpx) welded ignimbrite which forms the summit plateau of Monte Furru. An andesitic (Pl+Opx+Cpx±Hbl) dike/dome and a dacitic sill were emplaced contemporaneously with accumulation of the ignimbritic succession. No tectonic tilt is observable at Monte Furru.

Paleomagnetism

Paleomagnetism of the Monte Furru succession was previously investigated by *Assorgia et al.* [1994]. They concluded that the overall characteristic remanent magnetization (ChRM) declination pattern demonstrates a progression from NW to N directions from the base to the top of the succession. Some unanswered questions were raised by this study, such as the nature of an unusually large declination range (309° to 7°) in the lower flow (BO1) of the GIB, and the implications of some sites with anomalously low

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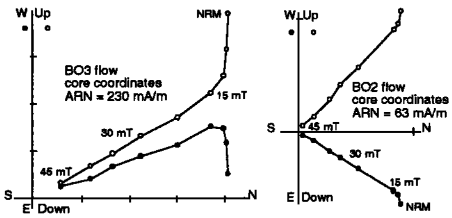

Figure 1. Orthogonal demagnetization plots of some samples from Monte Furru succession.

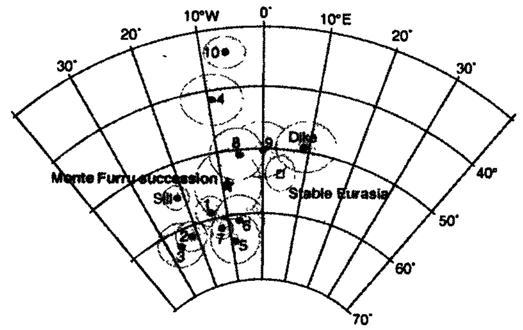

Figure 2. Paleomagnetic directions of flows of the Monte Furru sequence with α_{95} confidence limits. The direction computed from the Eurasian pole is indicated. Numbers refer to the stratigraphic order of flows.

inclinations. In addition, some directions from *Assorgia et al.* [1994] were obtained from only a small number of samples. The questions and concerns regarding the paleomagnetism of volcanic units at Monte Furru led to the acquisition of additional paleomagnetic data as part of this investigation.

The sequence of 12 volcanic flow units at Monte Furru was sampled with solar oriented drill cores along multiple vertical profiles, to avoid local magnetic anomalies. Natural remanent magnetization was measured with a JR4 Agico spinner magnetometer. Alternating field and thermal stepwise demagnetizations were employed with identical results. Demagnetization orthogonal plots and principal component analysis assisted determination of ChRM. *Fisher* [1953] statistics were used to process the data. For all the samples, magnetic saturation occurred at 150-300 mT and the Curie temperature is ~550-580°C, indicating titaniferous magnetite as the main magnetic carrier. Hysteresis loops indicate pseudosingle domain grains. For almost all samples, ChRM was isolated after removing a viscous and occasionally a secondary magnetization (Fig 1). The uppermost dacitic flow, struck by lightning at the sampling locations, required the use of the remagnetization circles method. Different sites within a given flow consistently gave indistinguishable directions at the 95% confidence interval. A mean direction for each flow using the sample data from each site is shown in Fig 2 and Table 1. Though directions of the upper flows are somewhat closer to N than those of the lower flows, the results do not indicate a definitive declination trend as described by *Assorgia et al.* [1994]. We suspect that the discrepancies between our studies may at least partly be explained by the sampling technique of *Assorgia et al.* (i.e., all cores for a given site derived from a single orientated block).

Geochronology

Sanidine occurs only in the GIB whereas biotite was found throughout the succession. Two variants of the $^{40}Ar/^{39}Ar$ technique were employed, both using an Ar-ion laser as the sample heating device: sanidine phenocrysts were dated individually by the focused-beam, total-fusion technique, while biotite phenocrysts in small populations (5-15 grains) were incrementally heated using a defocused laser beam ([*Deino and Potts* 1990; *Deino et al.*, 1990; *Deino et al.*, 1998] for analytical details). Sanidine from the Fish Canyon Tuff of Colorado was used as the neutron fluence monitor, with a reference age of 28.02 Ma [*Renne et al.*, 1998].

Five sanidine samples from different stratigraphic levels in the GIB were dated. Age-probability density diagrams of the dating results (Fig 3) indicates unimodal, gaussian-like distributions for each sample (MSWD's range from 0.72-1.1). The five concordant mean sample ages yield an overall weighted mean age of 18.18 ± 0.03 Ma (this excludes external errors in decay constants and the age of the standard, which would increase the overall error estimate of the $^{40}Ar/^{39}Ar$ ages by ~2% 1σ, [*Min et al.*, 2000]) This well-constrained result serves as the reference age to which the biotite dating results on the GIB and overlying units can be compared.

Biotite incremental-heating spectra are shown in Fig 4 with integrated and plateau ages indicated; plateau ages are also shown in Fig 5 in relation to the stratigraphy. Two aliquots of a biotite separate from each of five samples were dated. Most of the experiments yielded similar spectra, demonstrating concordance throughout the bulk of the ^{39}Ar release. However, a common tendency consisting of a stair-step decrease in the age of steps within the initial 5–30% of gas release was noted for most spectra. In a few cases, this was also accompanied by a clearly defined stair-step increase in age in the final 10-30% of ^{39}Ar release. Two explanations are the most likely: excess ^{40}Ar (a common interpretation of 'saddle shaped' spectra), or alteration. Excess ^{40}Ar appears unlikely in light of the high temperature of emplacement of at least one of the flow dated. Sample MF-11, which yielded spectra that are typical of this biotite suite, is from the uppermost, densely welded flow. It was therefore emplaced above ~600°C, the minimum welding temperature evaluated for a 15 m thick pyroclastic flow [*Riehle*, 1973], well above the blocking temperature of biotite (variable but likely less than 350°C, [*Harrison et al.*, 1985]). This suggests that excess ^{40}Ar entrapped in the biotite prior to

Table 1. Paleomagnetic directions at Monte Furru

Flow	D°	I°	k	α_{95}°	n/n_0	NRM	K	δ°
DA	351.4	38.6	200	3	13/13	14.0	20.3	15
Dike	9.2	49.8	127	4.3	9/9	1.44	35.0	17
Sill	338.1	55.6	826	4.3	6/9	0.56	13.7	10
IF2	0.2	50.6	110	4.6	9/10	2.49	6.4	9
IF1	354.6	51.2	118	4.2	10/10	1.98	5.8	6
MF4	348.6	62.0	908	1.4	11/12	1.64	3.3	7
MF3	353.2	61.4	114	3.9	12/12	0.44	5.6	6
MF2	350.6	64.1	120	4	11/12	0.39	5.1	9
MF1	351.0	42.1	235	4.5	5/5	0.17	6.2	15
BO3	340.2	63.1	131	3	18/22	0.58	3.0	11
BO2	341.2	61.7	229	2.3	18/21	0.14	3.0	10
BO1	344.9	58.3	99	2.2	43/47	0.22	3.3	5
Mean 1	351.0	55.2	62	5.3	12			
Mean 2	351.1	52.9	51	7.3	8			

k: Fisher precision parameter, n/n_0: number of samples used in analysis/number of measured samples, NRM in A/m, K: susceptibility in 10^{-3} SI, δ: angular distance between the VGP and the mean of the VGP. All VGP are non-transitional. Mean 1/2: mean direction computed with individual flows/by combining flows BO2-3, MF2-4, IF1-2.

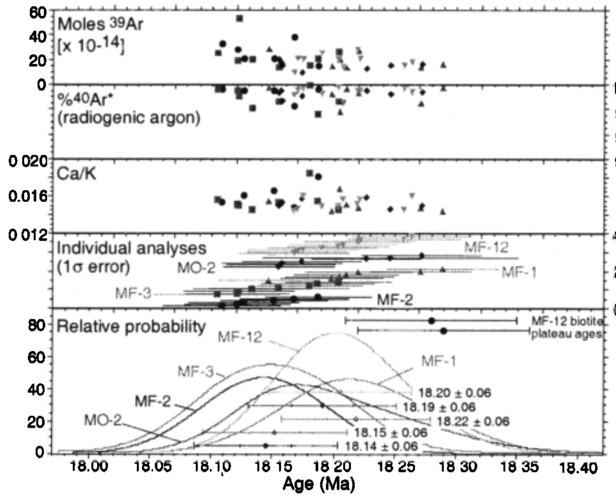

Figure 3. Age-probability density spectra for the single-crystal $^{40}Ar/^{39}Ar$ total-fusion analyses of six GIB sanidine samples. The weighted-mean age with 1σ standard error of the mean is shown for each sample; the outermost error bars show uncertainty including error in the neutron fluence parameter, *J*, (0.3 %). The two biotite plateau ages of the GIB are shown.

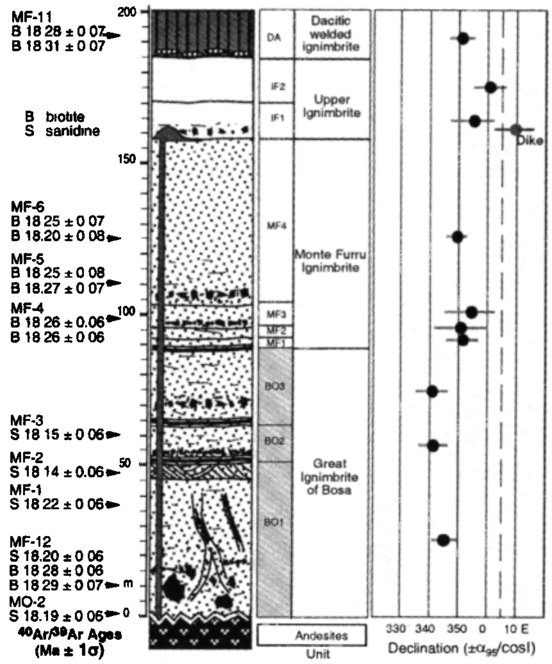

Figure 5. Age and paleomagnetic declinations of the volcanic succession of Monte Furru. Dashed line indicates the declination computed from the European paleomagnetic pole.

eruption would be rapidly lost during post-emplacement cooling of the flow. It is more likely that the discordance of the early steps, and of some of the final steps, records alteration of the biotite at some stage subsequent to crystal growth (conceivably as early as during pre-eruptive conditions in the magma chamber, or as late as surficial weathering of the outcrop). The alteration process has resulted in the preferential removal of K relative to $^{40}Ar^*$, leading to artificially old ages. The extent of this alteration process and its influence on the biotite plateau ages is fairly minor, however, as deduced from several lines of evidence: 1) Spectra are concordant throughout most of the gas release in all incremental-heating experiments, 2) Radiogenic contents are usually >95% $^{40}Ar^*$, 3) Microprobe analyses of biotite from the GIB yields a K_20 content of 8.5%, indicative of fresh igneous biotite composition, 4) Small-population aliquots pairs from each of five samples are concordant in plateau and integrated ages, indicating homogeneity in the sample separates, 5) Two aliquots of biotite from the GIB (sample MF-12) yielded plateau ages of 18.28 ± 0.07 and 18.29 ± 0.07 Ma, statistically indistinguishable from the sanidine reference age of 18.18 ± 0.03 Ma obtained from the same sample at the 95% confidence level, 6) The complete range of biotite plateau ages is just 110 ka (18.20 ± 0.08 to 18.31 ± 0.07 Ma), and all are statistically indistinguishable from each other. Weighted mean ages derived from the biotite plateaus for the three units dated (18.29 ± 0.05 for the GIB, 18.25 ± 0.03 for the Monte Furru ignimbrite, and 18.30 ± 0.05 Ma for the capping dacitic flow) differ by less than 50 ± 120 ky (2σ).

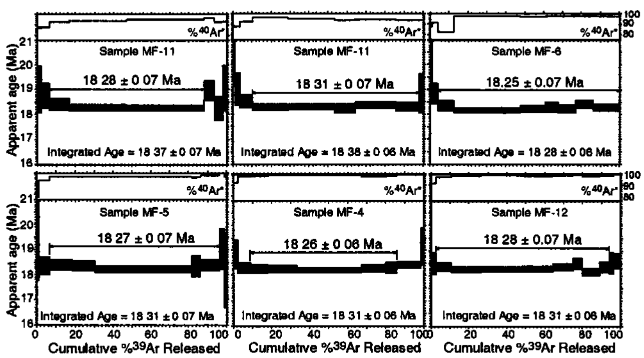

Figure 4. Incremental-heating apparent $^{40}Ar/^{39}Ar$ age spectra from biotite phenocrysts. Apparent-age uncertainties of the individual steps are shown at 2σ, uncertainties in the plateau age and integrated age are shown at 1σ. Incremental heating steps yielding less than 1% of the total ^{39}Ar were excluded from the data set. Plateaus were determined on the following basis: 1) Steps falling entirely within the first and last 10% of gas release were excluded, 2) steps at the ends of plateau segments deviating in age more than 1.8 times the weighted mean plateau age were excluded, 3) the plateau must have a minimum of three contiguous steps, 4) the plateau must have at least 50% of the total ^{39}Ar release, 5) the MSWD of the plateau ages must not exceed that explained by analytical scatter alone at the 95% confidence level.

Discussion

Conservatively, the biotite chronostratigraphy can be summarized by stating that the 200 m-thick Monte Furru volcanic pile likely accumulated within less than 200 ky. This relatively short accumulation interval precludes explanation of the variation of paleomagnetic directions by tectonic rotation during emplacement. Instead, the paleomagnetic scatter must be attributed entirely to paleosecular variation of the geomagnetic field. Our dataset displays a 26° range in inclination and a 31° range in declination, compatible with normal secular variation pattern.

A mean direction encompassing all Monte Furru flows can be calculated with the aim of averaging secular variation. The apparent polar wander path for Eurasia gives a lower Miocene pole located at 84°N, 156.3°E, A95=2.6° (*Besse and Courtillot* [in press]), predicting for Monte Furru a paleomagnetic direction D=3.9°, I=54.6°. The measured mean inclination (55.2°) agrees with the predicted value, although our declination implies a 13 ± 7° counterclockwise rotation with respect to Europe (95% confidence limit calculated from

Demarest [1983]). This calculation may be potentially refined by combining related flow directions before computing an average direction for a given timeframe. Several sets of successive flows with near identical lithologies bear indistinguishable paleomagnetic directions (BO2/BO3, MF2/MF3/MF4, IF1/IF2), suggesting that the flows in each set were emplaced within a short interval relative to the rate of secular variation. To avoid over-representing these sequences in an overall average, we combined these directions and calculated a new mean for the succession (mean 2, Table 1). This mean direction remains close to that calculated without averaging related flows, and again implies a 13° rotation with no latitudinal movement. Hence our results suggest that by 18.2 Ma Sardinia had not yet completed its rotation with respect to the Europe and a rotation of ~13° was forthcoming.

Scatter of the Virtual Geomagnetic Poles (VGPs), defined as the angular standard deviation (ASD) of the VGPs, can be used to help evaluate whether secular variation has been sufficiently averaged. The between-site ASD is 11.6° (8.8-17.1° 95% confidence limits). Due to the small number of VGP (eight) used in the calculation, this estimation remains tentative. We note that this value is slightly lower but still compatible with the 15-16° that is expected at the latitude of Sardinia [*McElhinny and McFadden*, 1997]. In addition, the mean paleomagnetic inclination is identical to that computed from the Eurasian pole, suggesting that paleosecular variation has been successfully averaged by this dataset.

Conclusion

The Monte Furru volcanic succession was emplaced within less than 200 ky, beginning at 18.18 ± 0.03 Ma. This rapid emplacement interval dictates that the variation in the paleomagnetic declination record be attributed to the influence of secular variation and not to tectonic rotation. The overall mean paleomagnetic direction of the volcanic succession indicates that by ~18.2 Ma Sardinia remained ~13° shy of its final rotation position.

Our results disagree with conclusions drawn from previous paleomagnetic-geochronologic studies on Sardinian volcanic rocks which placed the end of rotation at 19.5 Ma [*Montigny et al.*, 1981]. We believe that the results of this study may have been hindered by insufficient accommodation of the effects of secular variation as well as inaccuracy of the K-Ar dating. Our results, however, are in accord with those derived from paleomagnetic investigation of Sardinian sediments [*Vigliotti and Kent*, 1995; *Speranza et al.*, 1999].

Finally, it can be noted that all units at Monte Furru have normal polarity and were likely emplaced during chron 5En. The younger age limit for this chron of 18.281 Ma given by *Cande and Kent* [1995] is in slight conflict with the mean sanidine age reported here (18.18 ± 0.03 Ma). Either the chron age is miscalibrated or the sanidine age is slightly too young.

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