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Comment 'Unveiling ductile deformation during fast exhumation of a granitic pluton in a transfer zone' by Richard Spiess, Antonio Langone, Alfredo Caggianelli, Finlay M. Stuart, Martina Zucchi, Caterina Bianco, Andrea Brogi, Domenico Liotta

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In their paper, Spiess et al. (2021) published structural, geochronological, and EBSD data on one of the monzogranite apophyses (Capo Bianco) of the buried Porto Azzurro Pluton (island of Elba, Northern Apennines, Italy), a pluton emplaced in the upper crust ($P < 0.2$ GPa; e.g. Papeschi et al., 2019). The authors publish a new U/Pb age of 6.4 ± 0.4 Ma, associated to the thermal peak, and a U-Th/He apatite age of 5.0 ± 0.6 Ma, related to a T of 60 °C. Spiess et al (2021) use these ages to model the exhumation of the pluton controlled by the sub-horizontal Zuccale Fault, a fault with 6 km of horizontal displacement (ZF; Keller & Coward, 1996). Their structural dataset from the macro to the microscale and EBSD analyses relies on a small section (about 100 m wide) in the NE part of the Calamita Peninsula. Based on their documentation of (1) vertical dykes in the monzogranite, (2) vertical to low-angle top-to-the-E extensional faults, and (3) later NW-striking oblique faults, they interpret the Porto Azzurro Pluton as emplaced in an extensional to transcurrent tectonic setting, extrapolating their findings to the entire Eastern Elba.

It is well known that forward models of pluton emplacement and exhumation require an extensive dataset including structural, petrological, and radiometric constraints on the pluton, aureole rocks, and surrounding structures (e.g., Ramsay 1989; Vigneresse 1995; Stipp et al. 2004; John and Blundy 1993; Morgan et al. 2008; Morgan et al. 2013 among many others). Spiess et al. (2021) investigated a very limited outcrop of monzogranite (< 0.01 km^2) deriving constraints on the evolution of a pluton-aureole system extending for 60 km^2 in SE Elba (Musumeci et al., 2015). By doing so, they selected a very narrow set of lithologies, structures, and pluton-host rock relationships compared to the wide range of data obtained by studies that investigated the entire aureole in the last ten years (Mazzarini et al., 2011; Musumeci & Vaselli, 2012; Musumeci et al., 2015; Papeschi et al., 2017, 2018, 2019).

In general, we think that it is scientifically weak to build a geological model based only on observations from a few hundred square meters. This gives a very limited and partial view of the geological features for the emplacement of magma at regional scale, and represents a major point of weakness of Spiess et al (2021)'s work.

In the following we focus on two very important issues that deserve an exhaustive explanation and discussion: i) the relationships between the granite and the host rock in the section studied by Spiess et al (2021) as well as in the whole Calamita Peninsula, and ii) the exhumation model proposed by the authors.

- Granite and host rock relationships

Spiess et al. (2021) investigated a monzogranite body that they regard as a part of the Porto Azzurro pluton. However, they never clearly define its relationships with the Calamita Schist (host rocks) nor they provide a description of the structures in the Calamita Unit (Fig. 1a), widely described in Musumeci & Vaselli (2012), Papeschi et al. (2017), and Mazzarini et al. (2011) and necessary for a comprehensive definition of the geology of the area.

Spiess et al. (2021) cite left-lateral shear zones that appear to have a ductile to brittle evolution. However, quoting Smith et al. (2011) in the same Capo Bianco outcrop, these faults could be related to the internal dynamics to the intrusive system. According to Smith et al. (2011) *"Localized, high-temperature mylonitic fabrics are found within, and in close proximity to, igneous bodies such as the Barbarossa stock and the dikes and sills at Spiagge Nere, but these are likely related to transient thermal perturbations during igneous intrusion"*. Why the authors do not discuss these previous interpretations? It is unrealistic interpret the meaning of tectonic structures without a clear exposure of the host intrusive rocks. In a widely exposed pluton in the

Alps (Neves, Italy), Pennacchioni & Mancktelow (2007) investigated transcurrent shear zones showing that dykes and fractures act as precursors to shear zones, ultimately controlling their orientation and kinematics with respect to the regional stress field. They reached this conclusion thanks to the excellent exposure of Neves, with glaciated outcrops extending for several km^2. A structural analysis of this kind is not possible in the tiny outcrop of Capo Bianco, which is the focus of the paper (Fig. 1a). Moreover, there is no evidence on Elba of large-scale ‘transfer zones’ as those reported by the authors in their figure 2. The island is rather a monotonous stack of tectonic slices/units with W-dipping tectonic contacts without any lateral dislocation except for very local structure with displacements in the order of a few meters (Barberi et al., 1967; Babbini et al., 2001; Papeschi et al., 2021).

Particularly, in the section studied by Spiess et al. (2021), the monzogranite body and associated dykes crosscut the high-grade metamorphic foliation of the host rocks (Fig. 1b). This foliation preserves amphibolite- to greenschist-facies metamorphism linked to the main intrusion, documented by (i) syntectonic Bt + And + Crd + Fsp peak metamorphic assemblages overprinted by retrograde Ms + Chl and (ii) quartz microfabrics indicating high-temperature grain boundary migration overprinted by low-temperature deformation (Papeschi et al., 2017; Papeschi & Musumeci, 2019). Therefore, the monzogranite body investigated by Spiess et al. (2021) emplaced after the thermal peak and retrograde deformation in the host rocks. Why do the authors not describe nor consider these relationships?

Spiess et al. (2021) report several E-verging low- and high-angle normal faults. The authors do not report, however, coexisting structures present in the area and link these structures to ZF without any valid field or geochronological constraint. As shown in Fig. 1c, the Calamita (including dykes) in the area is affected by top-to-the-E deformation which includes the high-angle and low-angle top-to-the-E 'normal faults' reported by Spiess et al. (2021), but also high-angle top-to-the-W 'reverse faults' and top-to-the-E 'thrust faults'. Why do they ignore these structures? Both Papeschi et al. (2018) and Smith et al. (2011) classified this population of faults as Riedel shears, consistent with top-to-the-E sense of shear. Why did they not discuss these previous data? In particular, Papeschi et al. (2017, 2018) and Papeschi & Musumeci (2019) documented geometrically identical Riedel shears at all scales in the Calamita Unit, showing that they occur away from the ZF and associated with older ductile/brittle shear zones. How were the authors able to link these structures to ZF and separate them from the older fabrics, given they do not document the relationships between these structures and ZF and they do not provide direct geochronological constraints on these faults?

In second order, Spiess et al. (2021) report the occurrence of a 3 m thick cataclasite without any description of its meso- and microstructures. As shown in Fig. 1d, the top of the monzogranite is indeed brecciated, but what is the meaning of this breccia, which is displaced laterally only by a few meters and closes as a lens? Could it be another type of breccia, like a hydrothermal breccia? Without an in-depth documentation of its meso- to microstructures, it is not possible to distinguish these types of breccias. Can the authors provide valid and verifiable structural data in this regard?

- Exhumation model for the pluton emplacement

The emplacement depth of the Porto Azzurro pluton is a maximum depth, based on the available maximum metamorphic pressures ($P < 0.18$-0.20 GPa; e.g. Musumeci & Vaselli, 2012; Papeschi et al., 2019). There are currently no constraints on the shape and thickness of the unexposed pluton, nor we know its composition (Musumeci et al., 2015; Papeschi et al., 2017). Therefore, all the parameters used by Spiess et al. (2021), like depth = 6.5 km, thickness = 3 km, etc., are arbitrary and not justified. The real issue is, however, the incorrect assumption that cooling rates coincide with exhumation rates. In the upper crust, plutons cool down very quickly (e.g. Annen, 2011) as for the case of the nearby Monte Capanne pluton that cooled in just 250000 yr (Barboni et al., 2015). To calculate an exhumation rate, Spiess et al. (2021) assume a fixed thermal gradient of 100 °C/km that remains constant for 1.4 Ma, which is the age range between their ages (6.4 Ma U-Pb zircon and 5.0 Ma U-Th/He on apatite ages). This is a very anomalous high gradient and requires a discussion. Is this a geothermal gradient? Is this a local thermal gradient like the one observed nowadays in Larderello? Why do the authors not consider cooling? With these questionable assumptions, the authors obtain exhumation rates of nearly 4 mm/yr. Assuming that these rates and the emplacement depth of 6.5 km used by the authors is correct and considering the current pluton depth (at about sea level), the authors imply that at 5 Ma the pluton was at 2-3 km depth, before the ZF activity (post 4.9 Ma; see below). This also implies a post 5 Ma exhumation rate of 0.4 - 0.6 mm/yr, thus controlled by erosion. An exhumation driven only by erosion from early Pliocene onward deserves an exhaustive discussion.

Notably, Spiess et al. (2021) link the exhumation of the 6-7 Ma pluton to the ZF. However, recently published K-Ar radiometric data constrained the ZF activity as younger than 4.90 ± 0.27 Ma (Viola et al., 2018). The early Pliocene age of ZF is consistent with field studies and radiometric ages in the aureole of the pluton documenting the existence of 6.3 – 6.7 Ma shear zones, faults, folds, and intrusives that were crosscut by the ZF (Musumeci et al., 2015). Specifically, Spiess et al. (2021) neither reported nor used more than 10 age constraints published in the area, documenting ductile deformation coeval with magmatism at 6-7 Ma (Musumeci et al., 2011, 2015; Papeschi et al., 2017), overprinted by brittle deformation on thrust faults at 4.5-6.0 Ma (Viola et al., 2018). On this latter point, Spiess et al. (2021) ignore these findings and report outdated and disproved constraints of the activity of ZF to 5-7 Ma (e.g. Westerman et al., 2004). Why do Spiess et al. (2021) neglect these recent radiometric data?

Moreover, even if in contrast the currently available data, assuming that ZF controlled pluton exhumation, the authors do not explain how a 4 km exhumation is possible on a horizontal structure with a total displacement of 6 km (maximum vertical exhumation = 1.05 – 1.50 km assuming a dip of 10 – 15°). What the authors constrained are, therefore, only cooling ages for rocks that likely remained at the same depth as the thermal anomaly faded away, as already discussed by Papeschi et al. (2018).

With this comment, we wish to stress that the formulation of a geologically consistent model for the emplacement of plutonic rocks in Eastern Elba requires:

1) the detailed investigation of a wider area along with detailed meso and microstructural analysis and radiometric dating of tectonic structures;
2) a more rigorous use of the available structural, metamorphic, and geochronological constraints published in the Calamita area and on Elba.

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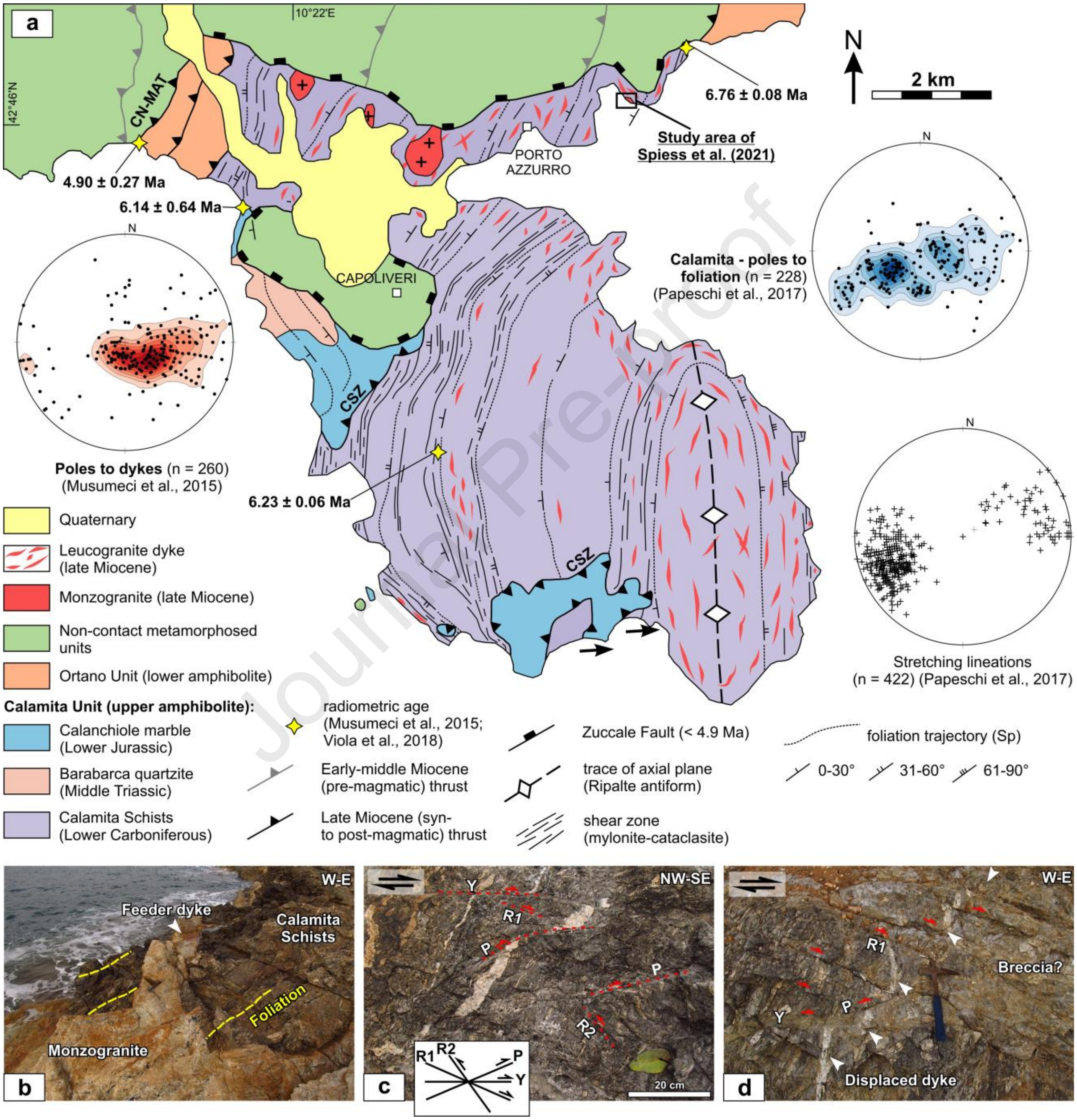
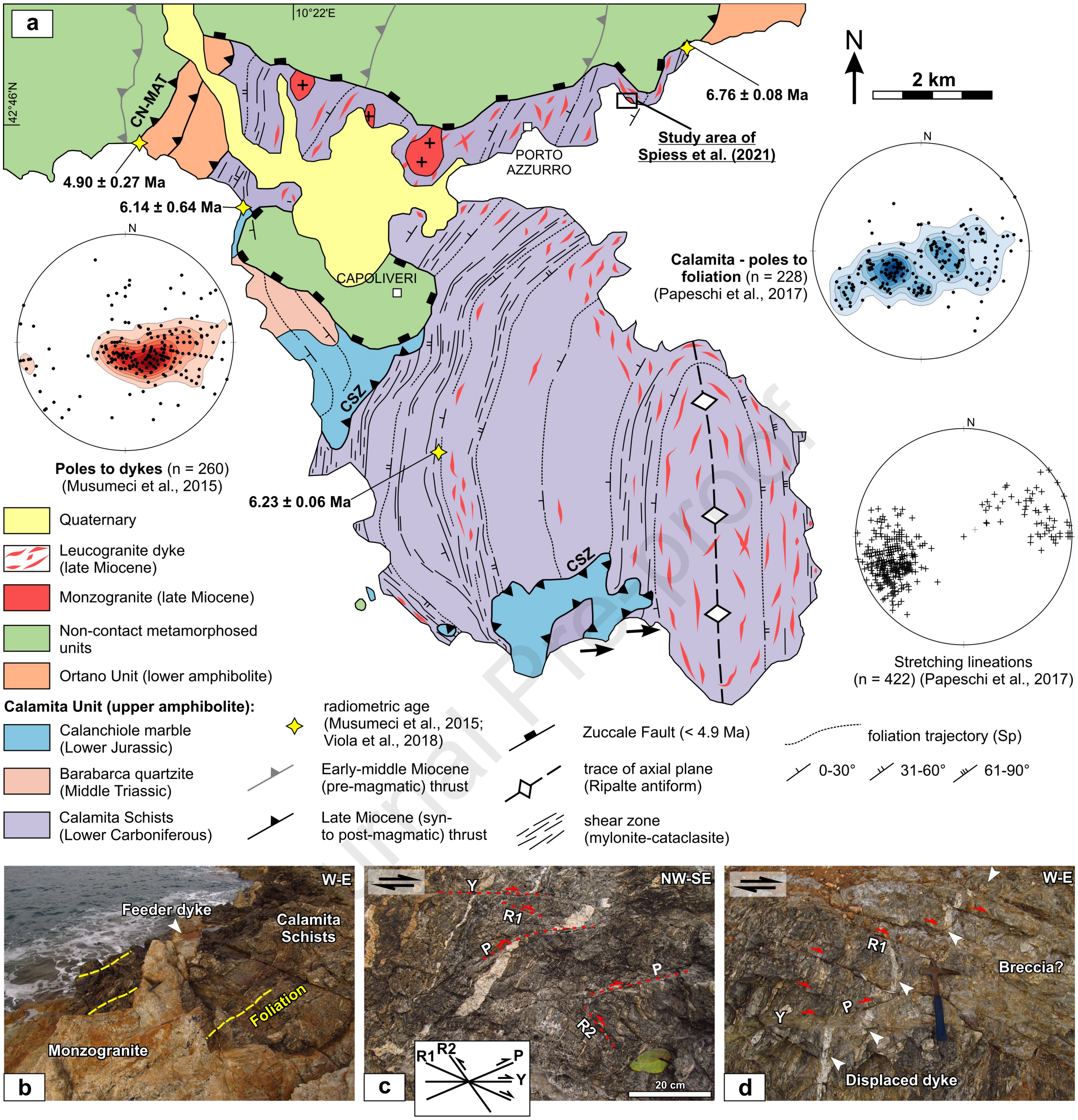


Figure 1 – Location and structures of the study area of Spiess et al. (2021). **(a)** Geologic framework of the Calamita Unit and the Porto Azzurro Pluton. Modified after Papeschi et al. (2017,

2018) and showing the age constraints by Musumeci et al. (2015) and Viola et al. (2018). **(b)** Intrusive contact of the monzogranite crosscutting the foliation in the Calamita Schists. **(c)** The population of faults in Capo Bianco comprises thrusts and normal faults that can be interpreted as Riedel shears following Smith et al. (2011) and Papeschi et al. (2017). **(d)** Is this brecciated body actually a cataclasite? The body closes as a lens, occurs entirely in the Calamita Schists and it is crosscut by faults with limited displacements.


a
10°22'E
42°46'N
CN-MAT
N
2 km
6.76 ± 0.08 Ma
Study area of Spiess et al. (2021)
PORTO AZZURRO
4.90 ± 0.27 Ma
6.14 ± 0.64 Ma
CAPOLIVERI
CSZ
6.23 ± 0.06 Ma
CSZ
N
Poles to dykes (n = 260) (Musumeci et al., 2015)
N
Calamita - poles to foliation (n = 228) (Papeschi et al., 2017)
N
Stretching lineations (n = 422) (Papeschi et al., 2017)
Quaternary
Leucogranite dyke (late Miocene)
Monzogranite (late Miocene)
Non-contact metamorphosed units
Ortano Unit (lower amphibolite)
Calamita Unit (upper amphibolite):
Calanchiole marble (Lower Jurassic)
Barabarca quartzite (Middle Triassic)
Calamita Schists (Lower Carboniferous)
radiometric age (Musumeci et al., 2015; Viola et al., 2018)
Early-middle Miocene (pre-magmatic) thrust
Late Miocene (syn- to post-magmatic) thrust
Zuccale Fault (< 4.9 Ma)
trace of axial plane (Ripalte antiform)
shear zone (mylonite-cataclasite)
foliation trajectory (Sp)
0-30°
31-60°
61-90°
W-E
Feeder dyke
Calamita Schists
Foliation
Monzogranite
b
NW-SE
Y
R1
P
P
R2
R1
R2
P
Y
20 cm
c
W-E
R1
Breccia?
P
Y
Displaced dyke
d

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: