Geodinamica Acta (Paris) 1998, 11, 5, 217–231

Large-scale Hercynian West-directed tectonics in southeastern Sardinia (Italy)

Paolo Conti[a*], Elisabetta D. Patta[b]

[a] Dipartimento di Scienze della Terra, Università di Siena, Via Laterina 8, 53100-Sienna, Italy
[b] Progetto CARG Regione Sardegna-Servizio Geologico d'Italia, Via Castello 24, 09010-Villamassargia (CA), Italy

(Received 24 May 1997; accepted 27 October 1997)

Abstract – Widespread Hercynian west-directed thrusting and west-facing folds, until now only reported in a limited area, are ubiquitous in the Sarrabus unit, southeastern Sardinia. Intense thrusting and imbrication in the higher tectonic levels of the Sarrabus unit potentially originated during west-directed thrusting of higher tectonic units, which have been eroded.The floor thrust of the Sarrabus unit, the Villasalto thrust, is a west-directed thrust that places the Sarrabus unit above the Gerrei and Meana Sardo units. East-west shortening in southeastern Sardinia followed north-south shortening in central Sardinia and internal deformation in the Castello Medusa-Riu Gruppa, Gerrei, Meana Sardo and Barbagia units. After restoration of movement along the Villasalto thrust, the Sarrabus unit is located east of the Gerrei and Meana Sardo unit. Therefore, it cannot be directly correlated with the Meana Sardo or the Barbagia units. © Elsevier, Paris

Hercynian tectonics / Sardinian Paleozoic basement / southeastern Sardinia

1. Introduction

It is usually assumed that during the Early Carboniferous, Hercynian collisional tectonics affected the Paleozoic of Sardinia with overall N-SH shortening (present day coordinates), and nappe transport to the south. This is well documented in central Sardinia by widespread NNE-SSW stretching lineations, by shear sense indicators along thrusts and southward facing folds [1–5]. While N-S shortening predominates in Central Sardinia, regional E-W shortening is the main deformation recorded in the low-grade metamorphic rocks of southern Sardinia to the west of the Tertiary Campidano graben in the Iglesiente-Sulcis area [6–8] (*figure 1*).

In southeastern Sardinia, east of the Campidano graben, shortening is only reported locally in the Sarrabus unit. First Carmignani & Pertusati [9] found evidence of E-W transport along the Villasalto thrust, the floor thrust of the Sarrabus unit, and then recognized west-facing folds in the Porto Tramatzu area, in the easternmost Sarrabus unit. Local scale west-directed thrusting (<1 km) is reported from the Punta Serpeddì area [10]. This scattered evidence of E-W shortening in southeastern Sardinia has been neglected, and it has been assumed that N-S shortening led to the emplacement of the Sarrabus unit onto the Gerrei unit and the Arburese unit (the westward continuation of the Sarrabus unit to the west of the Campidano graben), above the Iglesiente-Sulcis units [2, 11, 12]. Based on the assumption of southward nappe transport, the Sarrabus unit is usually correlated with the northernmost tectonic units outcropping north of the Flumendosa antiform: the Meana Sardo or Barbagia unit. The aim of this paper is to show that:

a) large-scale regional E-W shortening during Early Carboniferous occurred not only in the Iglesiente area, but also in southeastern Sardinia and affected the entire Sarrabus unit;

b) emplacement of the Sarrabus unit was from the East to the West;

c) westward nappe emplacement followed N-S shortening, deformation, and nappe stack formation in central Sardinia. The Sarrabus unit was emplaced above the Meana Sardo unit after it was thrust onto the Gerrei unit;

d) the Villasalto thrust is a west-directed thrust, forming the floor thrust of the Sarrabus unit. It was later reactivated locally as normal fault;

e) the Sarrabus unit cannot be correlated with any of the northernmost tectonic units of southeastern Sardinia now outcropping north of the Flumendosa

* Correspondence and reprints

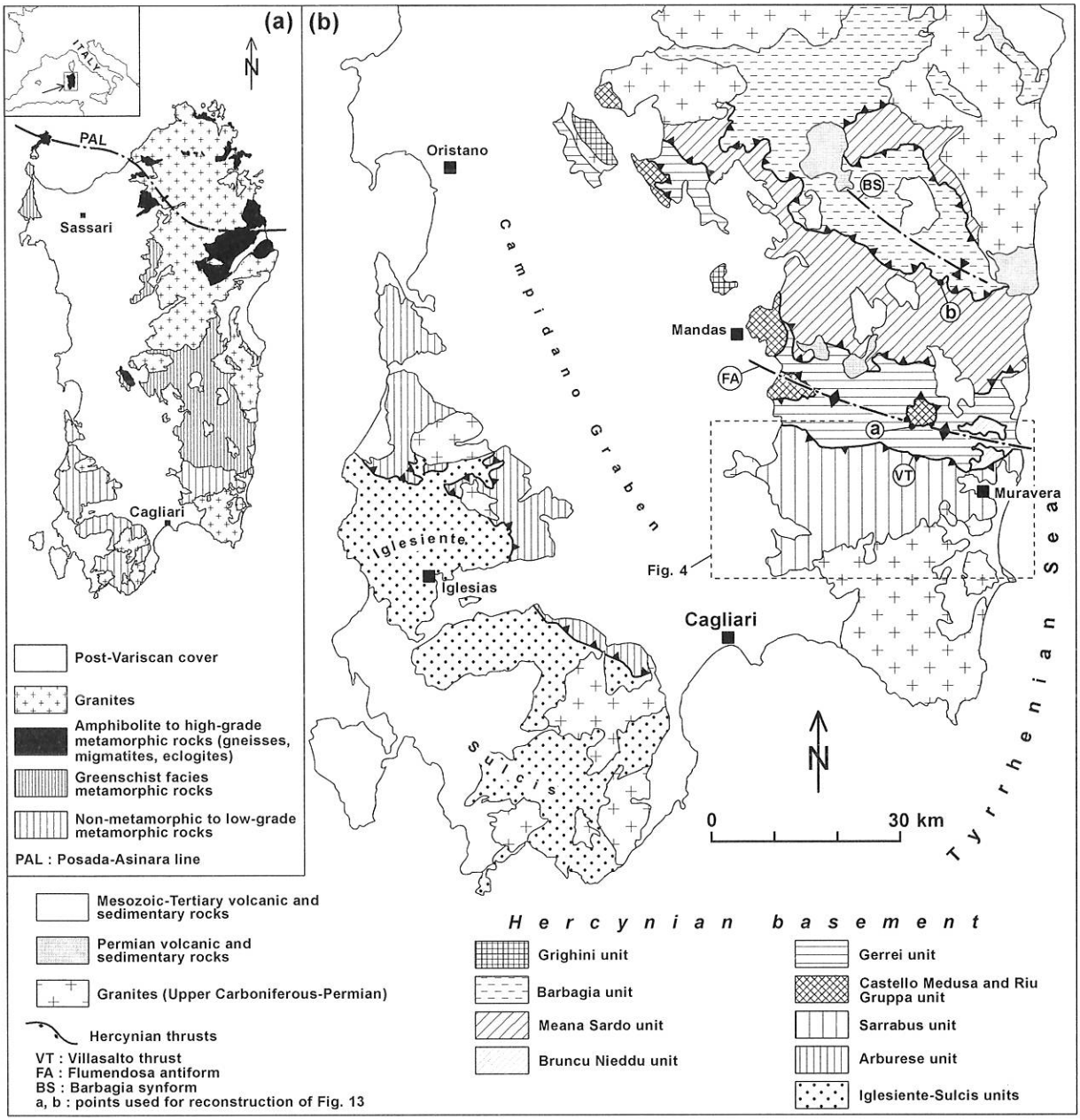


Figure 1. (a) Tectonic map of Sardinia. (b) Tectonic map of the Hercynian basement of southeastern Sardinia, after Carmignani et al. [43], modified.

antiform. Before deformation, the Sarrabus unit was paleogeographically located in an easternmost position with respect to the other tectonic units;

f) the Hercynian basement of southeastern Sardinia shows the same kinematic evolution as the Hercynian basement in southwestern Sardinia (Iglesiente-Sulcis units), with a N-S shortening event followed by E-W shortening. Westward transport of the Arburese-Sarrabus units may also be responsible for deformation in the underlying Iglesiente-Sulcis units.

2. Geological units of the Hercynian basement of SE Sardinia

Since its recognition [1, 13, 14], the nappe structure of the Hercynian basement of southeastern Sardinia has

been regarded as the result of a N-S continent-continent collision (present day coordinates) between the northern Armorican and the southern Gondwana margin in the Late Carboniferous. Following Cappelli et al. [15], the collision zone with remnants of oceanic crust is exposed in northern Sardinia along the Posada-Asinara line (*figure 1a*).

In central and southern Sardinia, collisional tectonics produced regional thrusting, nappe emplacement, greenschist facies metamorphism and open to isoclinal folding [2]. The following nappes were emplaced during continental collision (from north to south, *figures 1* and *2*): the Barbagia, Meana Sardo, Gerrei, Castello Medusa-Riu Gruppa, and the Sarrabus units. Late collisional deformation (*figure 2b*) generated km-scale upright synforms and antiforms striking NW-SE, refolding earlier foliations and folds. The larger tectonic features in south east Sardinia are the Flumendosa antiform and Barbagia synform developed during this subsequent stage of deformation.

Deformation associated with continent-continent collision was followed by late-orogenic extension and granite intrusion [2, 15, 16]. During granite emplacement, the Hercynian basement was affected by normal low-angle and strike-slip faulting, accompanying Late Carboniferous to Early Permian basin formation. Mesozoic-Cenozoic carbonate sequences unconformably overlie the Hercynian basement and show little evidence for Alpine deformation. This evidence is restricted to normal slip on N-S striking faults.

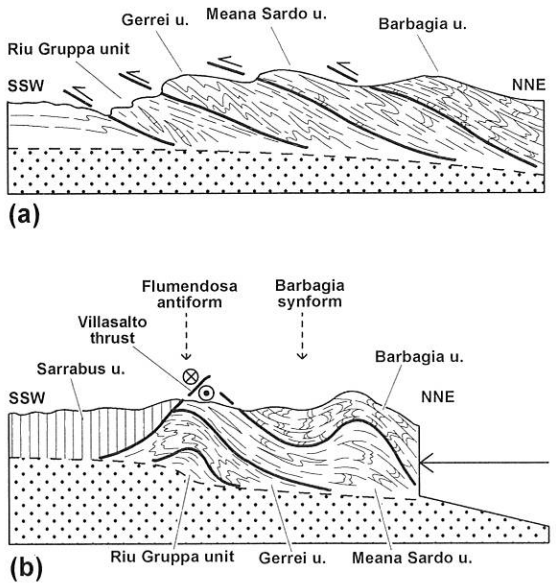


Figure. 2. Tectonic evolution of the Hercynian basement of SE Sardinia during continental collision, along a NNE-SSW profile. (a) Main nappe emplacement stage (D1). (b) Late stage D1 deformation.

All the main tectonic features of the Paleozoic basement of southeastern Sardinia were acquired during the Hercynian deformation phases. Dating of the youngest rocks involved in deformation and metamorphism and the older non-deformed sediments indicates an Early Carboniferous (Visean) time span for the Hercynian deformation [17–21]. Below, we deal only with Hercynian tectonic processes leading to nappe emplacement and major internal deformation in all tectonic units. We do not take into account post-collisional deformation (tectonic exhumation, low angle normal faulting, etc.) because it only had minor effects in the study area.

The nappe structure of the Hercynian basement of SE Sardinia is well established north of the Flumendosa antiform [1–3, 5, 12]. The Barbagia unit is in the higher position and overrides the Meana Sardo unit, the Gerrei unit and the Castello Medusa-Riu Gruppa unit (*figures 1* and *2*). All these nappes show well-developed NNE-SSW stretching lineations, "top-to-the-south" shear sense indicators along main thrusts and strongly non-cylindrical isoclinal folding. Deformation was contemporaneous with greenschist facies metamorphism.

Figures 1 and *2b* show that tectonic units do not outcrop symmetrically with respect to the Flumendosa antiform. The Barbagia and Meana Sardo units outcrop only in the northern limb. The Sarrabus unit directly overlies the Gerrei unit, along the Villasalto thrust in the southern limb. If we assume N-S tectonic transport throughout Hercynian collisional tectonics, the Sarrabus unit must necessarily be correlated with the northernmost Meana Sardo unit [12] or with the Barbagia unit [22]. To decide whether the first (Sarrabus unit=Meana Sardo unit) or the second interpretation (Sarrabus unit=Barbagia unit) is more plausible, it is crucial to consider the position of the Bruncu Nieddu unit (*figure 1*). The Bruncu Nieddu unit occurs in two outcrops in the hinge zone of the Flumendosa antiform. The first occurrence is an isolated "Klippe" on top of the Gerrei unit. The second occurrence is located on top of the Gerrei unit and below the Sarrabus unit, near the Villasalto thrust. If we interpret the Bruncu Nieddu unit as a higher slice of the Gerrei unit [3] the Sarrabus unit must be correlated with the Meana Sardo unit. Gattiglio and Oggiano [22] demonstrate that the Bruncu Nieddu unit is not part of the Gerrei unit, but that it must be correlated with the Meana Sardo unit. Since the Sarrabus unit overlies the Bruncu Nieddu unit, it also overlies the Meana Sardo unit. Assuming a N-S nappe transport, the Sarrabus unit must therefore be correlated with the northernmost Barbagia unit.

In both interpretations problems occur, namely:

a) Mismatch of the stratigraphy: the Cambrian-Lower Ordovician succession in the Sarrabus unit differs from those in the Meana Sardo and in the Barbagia units. Thick turbiditic sandstone beds which are characteristic of the Sarrabus unit are missing from the Barbagia and Meana Sardo units, where shale and micaschist are the predominant lithologies. Gabbroic intrusions usually

found in the Cambrian succession of the Meana Sardo unit are missing in the Cambrian of the Sarrabus unit. Ordovician basic to intermediate volcanic rocks of the Meana Sardo unit are not present in the Sarrabus unit.

b) Differences in the internal deformation related to the collisional tectonics: both the Meana Sardo and the Barbagia units show well-developed NNE-SSW stretching lineations, km-scale isoclinal folds, mylonites, and greenschists facies metamorphism. The floor thrusts of both nappes are a mylonite-rich "top-south" thrust. All these features are missing from the Sarrabus unit.

As will be shown later, the tectonic evolution of the Sarrabus unit is different as compared with the northernmost Gerrei, Meana Sardo and Barbagia units. Thus, both previously made correlations have to be rejected.

In the following we distinguish 3 deformation events:

D1: emplacement of the Gerrei, Meana Sardo and Barbagia units;

D1':emplacement of the Sarrabus unit;

D2: post-collisional deformation.

3. Tectonic evolution of the Sarrabus unit

In this paper we refer to the southernmost tectonic unit of the Hercynian nappe stack of southeastern Sardinia as the Sarrabus unit (*figure 1*). This unit outcrops south of the Villasalto thrust and is juxtaposed in the south against the Late Hercynian granite intrusion of southern Sardinia (Sarrabus granite). Westward it disappears below the Tertiary volcanic and sedimentary rocks of the Campidano graben. Carmignani et al. [13] first named this unit "Genn'Argiolas unit", a name widely adopted in the geological literature. Recent detailed field work in the Muravera area [23] allowed for a further subdivision of the Sarrabus unit into three "sub-units", and the usage of the name "Genn'Argiolas unit" was restricted to the sub-unit that outcrops at Mount Genn'Argiolas. Our Sarrabus unit therefore corresponds exactly to the "Genn'Argiolas unit" of Carmignani et al. [3].

The Cambrian to Lower Carboniferous succession outcropping in the Sarrabus unit [10, 24–27] starts with thick (>500 m) siliciclastic turbidite deposits, mostly sandstones and shales, of the San Vito formation (?Middle Cambrian-Arenig) (*figure 3*). Up section follow Middle Ordovician acidic to intermediate volcanic rocks ("Porfidi Bianchi" and "Porfidi Grigi" formations). The contact between the San Vito formation and the overlying Porfidi Bianchi and Porfidi Grigi formations is marked by an angular unconformity ("Fase Sarrabese" of Calvino [26]), well exposed along the Rio Ollastu and north-east of Genn'Argiolas. Along the contact conglomerates (Rio Ceraxa conglomerates) outcrop, the overlying sandstone and shale-rich sequence can be divided into three formations: the lowermost Punta Serpeddì formation (Caradoc-Ashgill), the Tuviois formation (Ashgill), with limestone intercalations in the upper part, and uppermost Graptolite shales (Silurian)

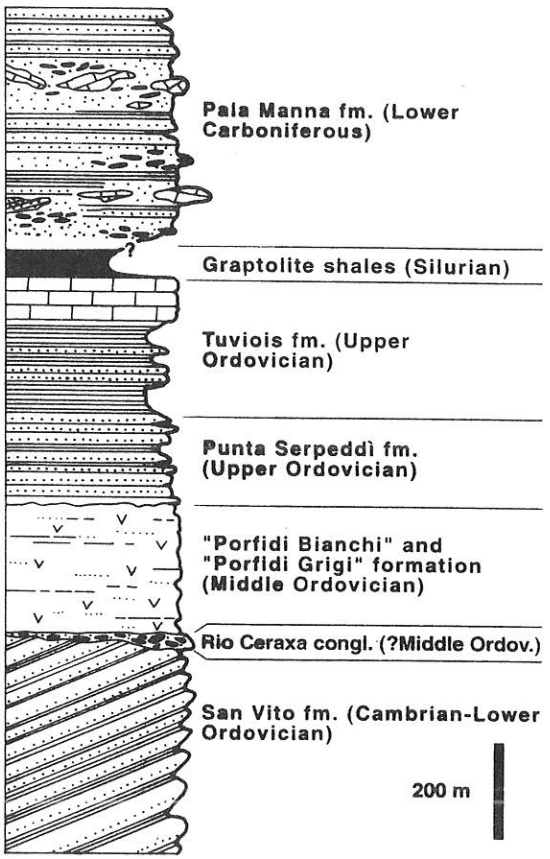


Figure 3. Cumulative stratigraphic section in the Sarrabus unit.

(black shales and limestones). The youngest sediments exposed are conglomerates, sandstones and shales of the Pala Manna formation (Lower Carboniferous). This formation, which frequently includes blocks of younger rocks, is interpreted as a thick succession of clastic material accumulated in foredeeps during synorogenic deposition. The relationship between the Pala Manna formation and the older succession is unclear. In the eastern Sarrabus unit, east of M. Genis, contact is always tectonic. Between M. Genis and Genn'Argiolas the contact is represented by the Bruncu Istrias fault (*figure 4*). East of Genn'Argiolas the Pala Manna formation is limited by D1 thrust (*figure 5*). In the western Sarrabus unit, between M. Genis and Dolianova, the nature of the contact is not studied in detail. Distinctive, thick (>100 m) Devonian limestones, which are characteristic of the adjacent Gerrei and Meana Sardo tectonic units, are missing. It is therefore unresolved whether the contact is: (a) a primary stratigraphic contact (unconformity, disconformity?), (b) a D1 thrust plane, (c) a D2 low angle normal fault.

All these rocks were deformed during the Hercynian orogeny. No geochronological data are available for deformation events in the Sarrabus unit, and the timing

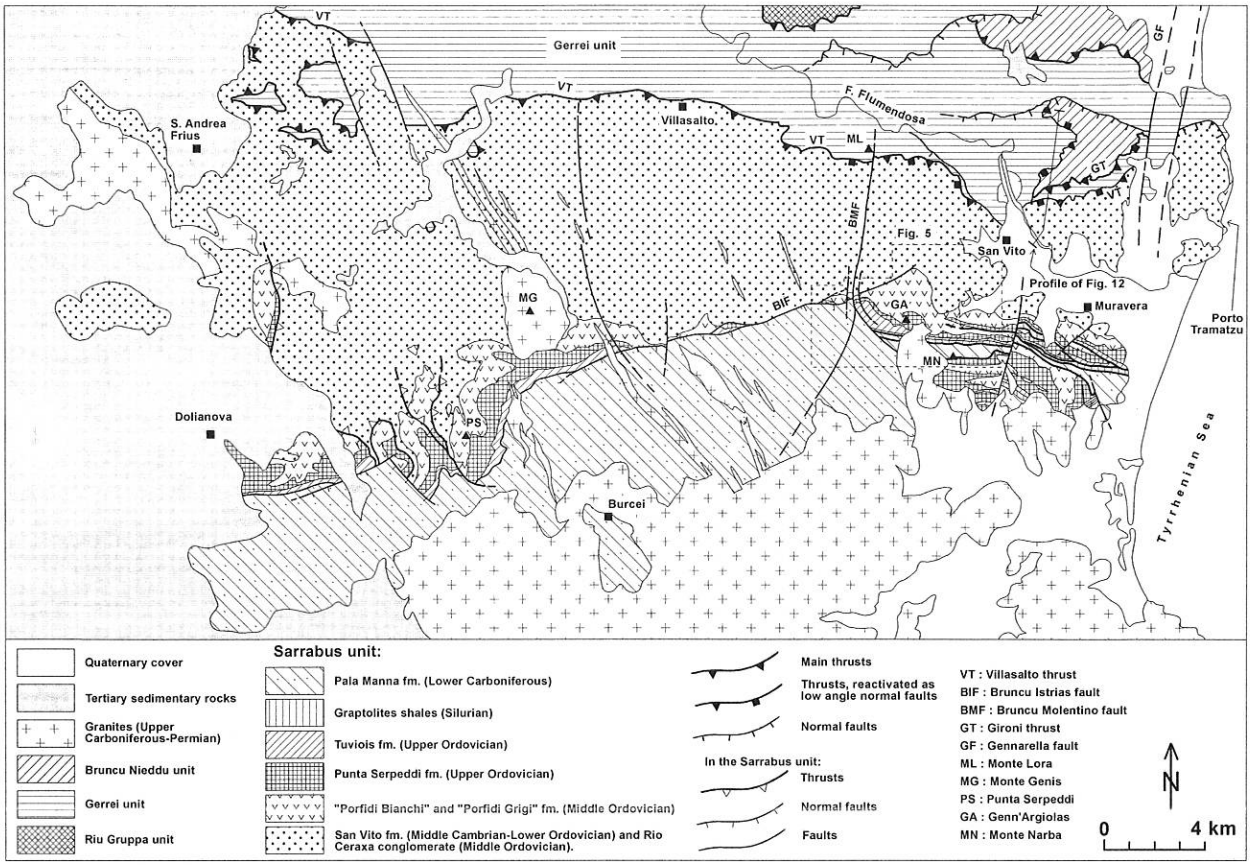


Figure 4. Geological map of the Sarrabus unit and adjoining areas. Compiled using own mapping and maps of Calvino [26, 44], Carmignani et al. [3], Barca and Maxia [10], Barca et al. [11, 45], Gattiglio and Oggiano [22]. See [10] for profiles in the Punta Serpeddì area. Location of *figure 5* and profile of *figure 12* are indicated.

of deformation is only constrained by the younger sediments involved, i.e. the age of calcareous blocks resedimented in the Pala Manna formation with Fammenian (Upper Devonian) age [24] and by older not-deformed Stephanian (Upper Carboniferous) deposits from adjoining areas [17, 28].

Precambrian metamorphic basement is not known in Sardinia. A Precambrian age has been proposed by Pittau Demelia and Del Rio [29] for the Bithia formation of southeastern Sardinia, but this proposition is not widely accepted [30]. In the Sarrabus unit, possibly Precambrian metamorphic rocks are found as clasts within Ordovician volcanic rocks (*figure 6a*). Clasts of metamorphic rocks are often found in the "Porfidi grigi" and they have a higher metamorphic grade than the low-grade metamorphic rocks of the Sarrabus unit. These metamorphosed rock fragments show a well-developed schistosity with fine alternating quartz and muscovite-biotite layers, which are not observed in the underlying San Vito formation. This implies that the fragments cannot be derived from the San Vito formation, rather they must represent an older (Precambrian) metamorphic basement beneath the San Vito formation of the Sarrabus unit.

3.1. Deformation contemporaneous with nappe emplacement (D1')

D1' is the main deformation phase in the Sarrabus unit, with folding, development of stretching lineations, thrusting and regional metamorphism. Internal deformation and metamorphism are less than in the Barbagia, Meana Sardo, Gerrei, and Castello Medusa-Riu Gruppa units.

Folding is manifested in ubiquitous large scale (m- to km-scale) open to isoclinal folds, with N-S oriented axes (*figure 7a*) and flat-lying axial planes. D1' folds are usually very well developed in the Cambrian sandstones of the San Vito formation. A large-scale west-facing fold was reported by Carmignani and Pertusati [9] in the Porto Tramatzu area. In contrast, our investigations indicate west-facing folds in the whole Sarrabus unit.

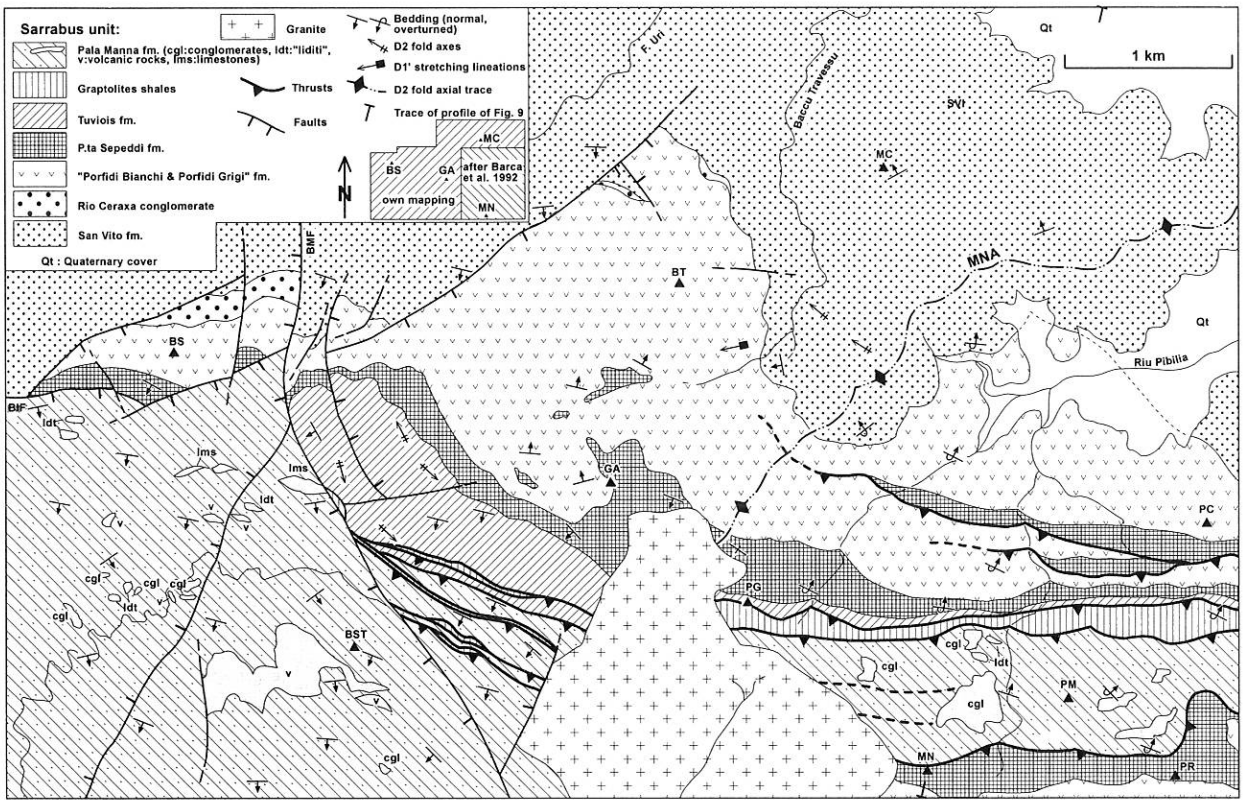


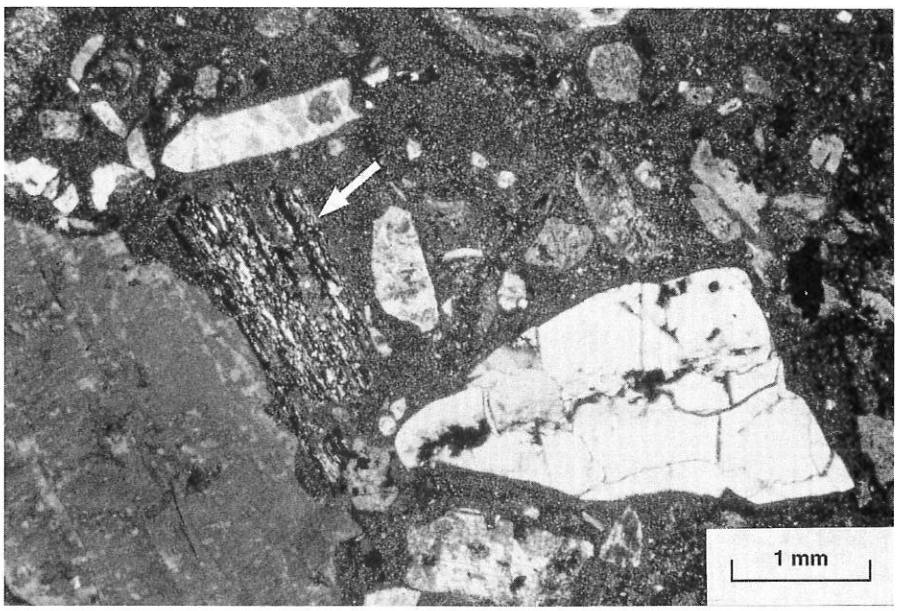
Figure 5. Geological map of the eastern Sarrabus unit in the Genn'Argiolas area, west of Muravera. See *figure 4* for map location. BMF: Bruncu Molentino fault, BIF: Bruncu Istrias fault, BS: Bruncu Su Sparau, BST: Bruncu Su Tuveraxiu, BT: Bruncu Tineddu, GA: Genn'Argiolas, MC: M. Niu Crobu, MN: M. Narba, PC: Punta Is Crabus, PG: Punta Gennedidu, PM: Punta Mallone, PR: Punta Ruggeri, MNA: M. Narba antiform.

D1' fold shape changes along an E-W profile in the Sarrabus unit. In the western and central part of the Sarrabus unit D1' folds are usually cylindrical, with N-S striking axes and flat-lying axial planes. In the easternmost part, between San Vito and Porto Tramatzu, folds have flat-lying axial planes, but they are no longer cylindrical and occur together with north- and south-facing folds (*figure 7b*). Because facing directions vary over 180°, including north, west and south, a regional "top-west" transport direction is inferred. Non-cylindrical D1' folds in the easternmost Sarrabus unit are therefore not the result of superposed folding, but are due to progressive fold axes reorientation during D1' deformation ("sheath folds"). Non-cylindrical D1' folds occur only in the easternmost Sarrabus unit. A large-scale (>40 km) non-cylindrical recumbent fold reported by Maxia [31] in the central Sarrabus unit is not recognised.

D1' stretching and mineral lineations are not very common in the Sarrabus unit. They can be found only along thrust planes, but they are widespread in the eastern part of the unit, near Porto Tramatzu (*figure 4*, *figure 8*). Here stretching lineations can be observed in Ordovician volcanic rocks ("Porfidi Grigi" formation) marked by pressure shadows near porphyroclasts of volcanic quarz. D1' stretching lineations are almost east-west oriented.

Metamorphic grade is very low during D1': anchi- to epizone [32]. Only recrystallization of sericite occurred and no substantial textural or microstructural changes were observed. An increase in temperature during metamorphism can be traced from west-east. In the central-western part of the Sarrabus unit (west of Genn'Argiolas) sericite grows with no or weak preferred orientation. In a thin section and at outcrop scale no penetrative schistosity or cleavage is observed and all the primary features of rocks are preserved (*figure 6a*). Cleavage development is restricted to the hinge zone of D1' folds. In the eastern part of the Sarrabus unit (east of Genn'Argiolas) recrystallized sericite and white mica grow along cleavage planes (*figure 6b*). Cleavage is also well developed on the outcrop scale. In this area area some features of low-temperature crystal plasticity in quartz are recognisable, as undulose extinction and deformation bands. Syntectonic recrystallization involv-

(a)



(b)

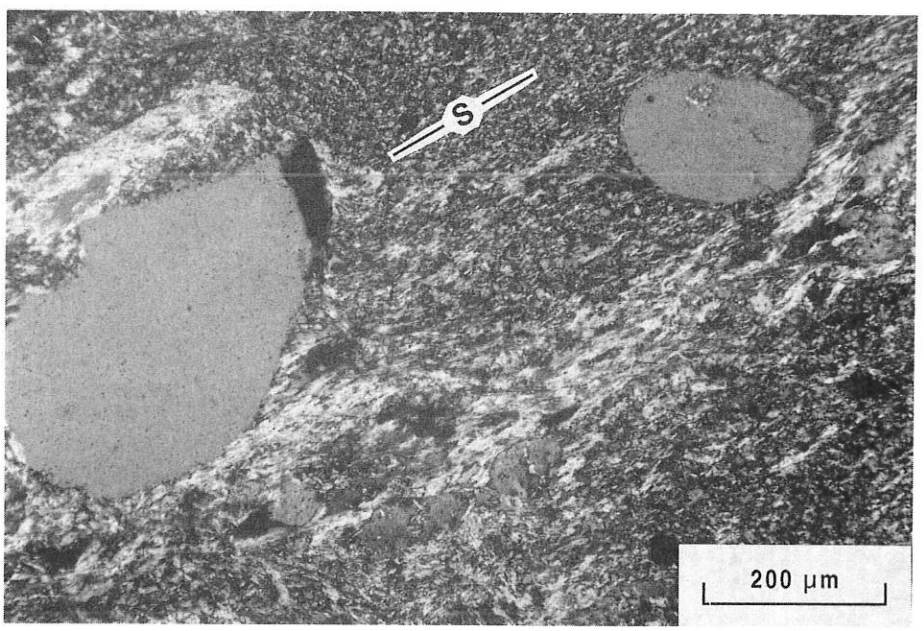


Figure 6. (a) "Porfidi grigi" formation, Riu Baccu Malu, south of Bruncu Tineddu, Sarrabus unit. Crossed polarised light. No foliation develops, note a clast of metamorphic rock (arrow) in the fine-grained devitrified volcanic matrix. (b) "Porfidi grigi" formation, Porto Corallo, crossed polarised light. Shape preferred orientation of mica defines a spaced foliation (S).

ing bulging and subgrain rotation occurred. No crystallographic preferred orientation developed.

During D1' deformation, thrusts developed in the Sarrabus unit in the Punta Serpeddì area, in the area north-east of Dolianova and between Muravera and Genn'Argiolas (*figures 4*, *5* and *8*). At Punta Serpeddì and north-east of Dolianova D1' thrust planes are flat-lying or E-dipping and strike north-south, the transport direction is "top-west" [10].

South of Muravera intense west-directed thrusting formed a complicated imbricate zone. In cataclastic rocks along thrust planes silver deposits, mined in the last century, occur (Monte Narba mining district) [33–35]. Between Genn'Argiolas and Bruncu su Tuveraxiu

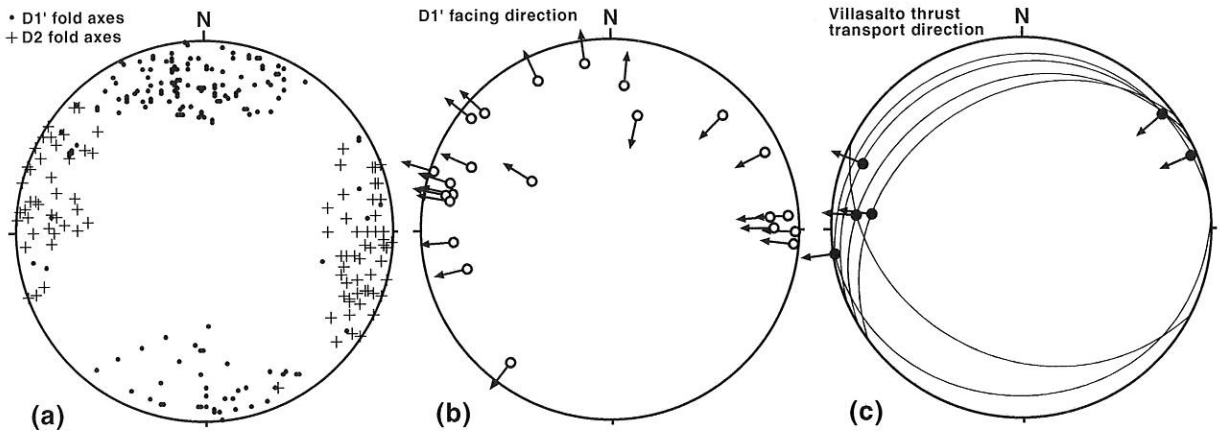


Figure 7. (a) D1' Fold axes (n = 193) and D2 fold axes (n = 116) in the Sarrabus unit. Own data and data from Carmignani and Pertusati [9] and Checchi and Duchi [46]. (b) Facing direction of D1' folds in the eastern Sarrabus unit. Arrows point to facing direction (direction normal to fold axis, in the fold axial plane or foliation, pointing towards younger beds). (c) D1' shear senses along the Villasalto thrust. Great circles: thrust plane attitude, arrows: transport direction of the hanging wall.

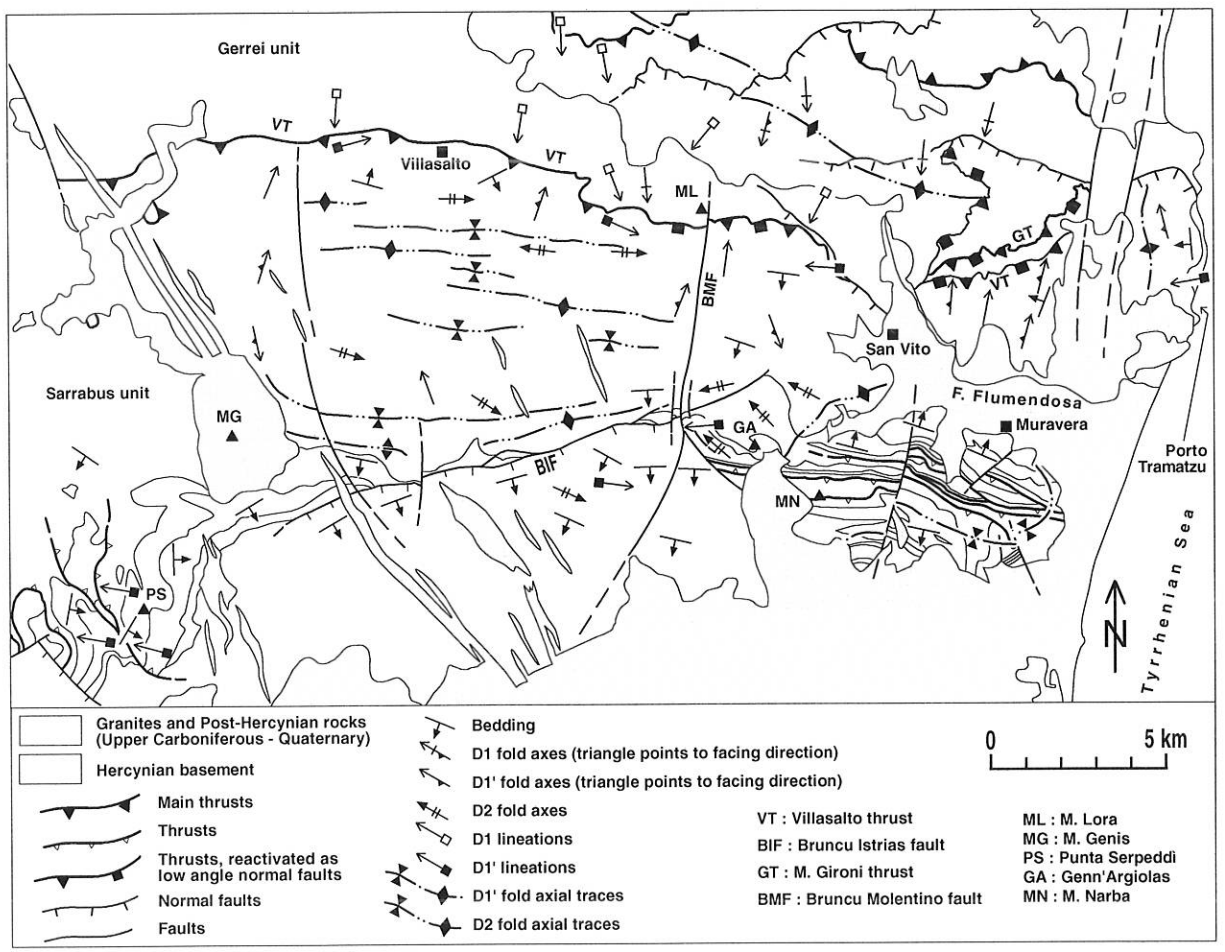


Figure 8. Structural map of the Sarrabus unit and adjoining areas.

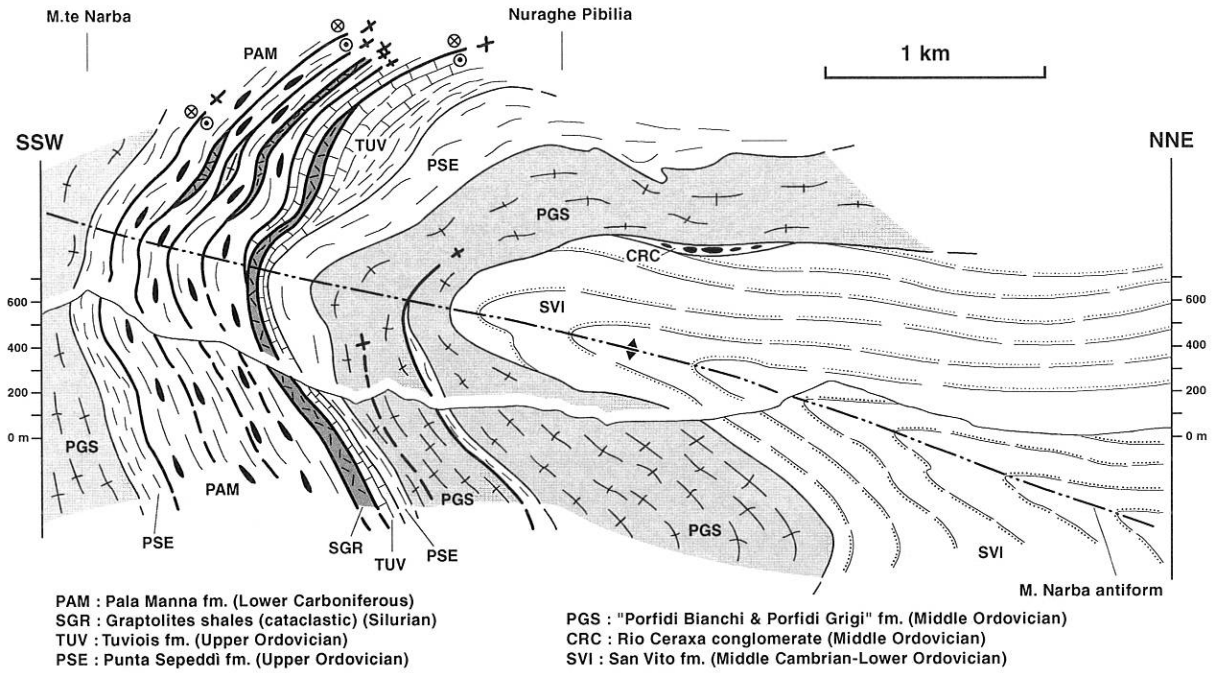


Figure 9. Profile in the eastern Sarrabus unit. Profile trace in *figure 5*.

(*figure 5*), D1' thrusts strike NW-SE and dip toward the SW. The uppermost imbricate sheets, consisting of sandstones and conglomerates of the Pala Manna formation, moved westward with respect to the northernmost (underneath) Cambrian-Ordovician succession. Due to a large scale D2 fold with NW-dipping axial plane (Monte Narba antiform, *figure 5*, *figure 9*) at P.ta Gennedidu, bedding and D1' thrusts are vertical. Further to the east of P.ta Gennedidu, D1' thrusts and the Cambrian-Ordovician succession occur in the overturned limb of the Monte Narba antiform. Thrust planes dip north. The Cambrian-Ordovician succession exposed along the Riu Pibilia is overturned and lies on top of the southernmost imbricate zone. Since the D2 fold axis of the Monte Narba antiform is WNW-ESE oriented, and almost parallel to the transport direction of the D1' thrusts, "top-W" thrusts occur west (i.e. above) of the axial plane of the Monte Narba antiform, and apparent "top-E" along overturned thrusts are found eastward (i.e. below) (*figure 10*).

Our interpretation is in contrast with Barca et al. [11] who attribute north-dipping thrusts in the eastern Sarrabus unit to D2 deformation and SSW-directed transport, and interpreted the Monte Narba antiform and the thrusts to be contemporaneous. In the Barca et al. [11] interpretation, the thrust planes represent a trailing imbricate fan structure below the Monte Narba antiform and the deformation of the Lower Carboniferous deposits of the Pala Manna formation in the Sarrabus unit is also ascribed to D2. However, *figure 5* and profile of *figure 9* clearly show that: (a) north-dipping thrusts in the Sarrabus unit east of Genn'Argiolas are D1' thrusts now in an overturned position due to the D2 Monte Narba antiform, (b) all thrusts have a "top-west" transport direction if they are back-rotated in their originally horizontal position, (c) all thrusts were originally in a higher position with respect to the Cambrian-Silurian succession along the Riu Pibilia and in the Genn'Argiolas area. Consequently, thrusts in the imbricate zone, south of Muravera, are not duplex structures emerging from beneath the Sarrabus unit, but they represent the higher structural level of the unit now exposed. The severe shortening and the complicated structure of the area imply that the Sarrabus unit is not

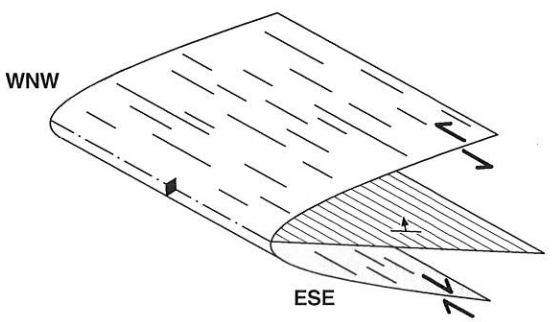


Figure 10. Sketch showing folded thrust plane around the D2 Monte Narba antiform (see also *figure 9*). Above the D2 fold axial plane "top-west" shear sense occur, below the axial plane "top-east" shear sense indicators are present.

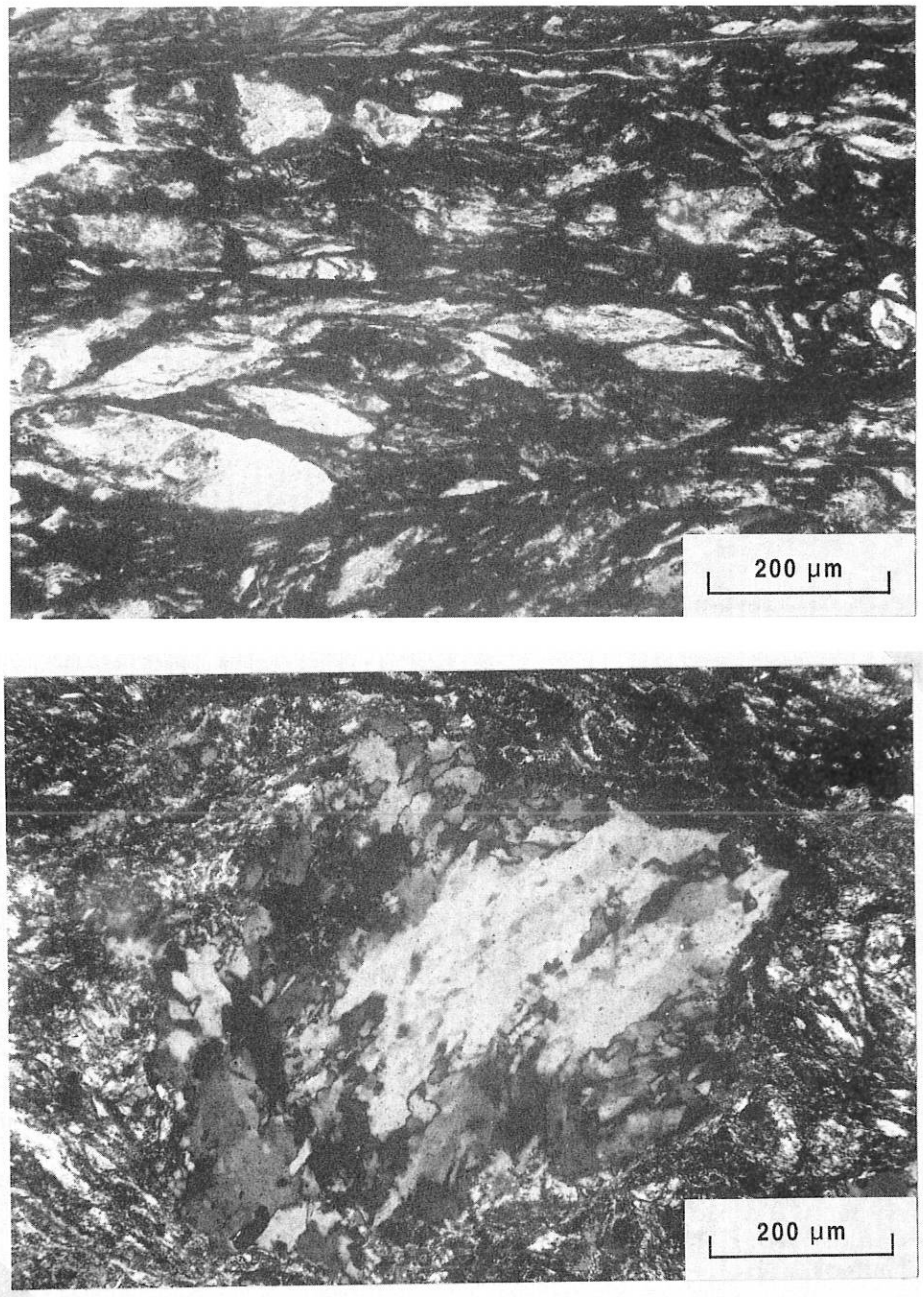


Figure 11. (a) Foliated cataclasite from the Villasalto thrust, near S. Andrea Frius, UTM coordinates NJ16787165. Plane polarised light. (b) Large quartz clast from quartz-mylonite in the cataclasite of the Villasalto thrust, same outcrop as in (a). Crossed polarised light. Clast shows dynamic recrystallization through bulge nucleation and subgrain rotation.

the highest nappe of the Hercynian pile in SE Sardinia which was passively translated above the foreland area; higher tectonic units (now eroded) were present, whose transport to the west produced the imbricate zone. The involvement of the Lower Carboniferous clastic deposits into the deformation also occurred during D1'.

3.2 The Villasalto Thrust

The Villasalto thrust [9] is a S-dipping D1' thrust, that places the Sarrabus unit above both the Gerrei unit (mostly Silurian and Devonian limestones and shales

below the thrust) and the Bruncu Nieddu unit (mostly sandstones and conglomerates). Shear sense indicators in cataclasites suggest west-directed transport along the thrust (*figure 7c*).

Cataclasis is the primary deformation mechanism operating within the thrust. Cataclastic flow produced fine-grained foliated black cataclasites (*figure 11a*) derived from both hanging-wall (mostly sandstones) and footwall rocks. The cataclasite matrix is made of very fine-grained muscovite, graphitized carbonaceous matter and Fe-oxides; larger feldspar and quartz clasts are common.

Evidence for low-temperature crystal plasticity in the cataclasites such as undulose extinction, deformation bands formation and subgrain rotation is only restricted to large quartz porphyroclasts (1–5 mm) (*figure 11b*). Clasts in cataclasites are often fragments of greenschists facies quartz mylonites now boudinaged in the fine-grained black matrix, implying that quartz at least during latest stages of deformation is stronger than the matrix. This suggests a change in the deformation mechanism during activity along the Villasalto thrust: was followed by cataclastic flow. It is not clear whether change of the deformation mechanism is due to cooling during deformation or to syntectonic reactions in the fine-grained matrix leading to strain softening [36, 37].

The thickness of cataclasite along the Villasalto thrust ranges from zero to >400 m near Villasalto. The cataclasites frequently contain sandstone lenses of the overlying San Vito formation and limestone lenses of the underlying Gerrei nappe. These lenses can be up to 700 m long.

As pointed out by Carmignani and Pertusati [9] the Villasalto thrust is folded by D2 folds. From M. Lora eastward, the Villasalto thrust is locally reactivated as a normal fault and cuts D1 and D1' folds from both the Genn'Argiolas and the Gerrei Nappe. Cataclasites again developed in this deformation, overprinting earlier fault rocks.

3.3 Late Hercynian folding (D2)

After E-W shortening (D1' phase) the Sarrabus unit is affected by D2 folding. D2 folds range from cm- to km-scale, and are usually upright cylindrical open to gentle folds, with NNE-SSW trending fold axes (*figure 7a*). D2 folding did not substantially change the D1' structure and most of the Sarrabus unit retains its normal attitude with younging direction upward. Since D2 fold axes are at a high angle to D1' fold axes, no significant scattering trend of D1 fold axes occured. Only between Muravera and Genn'Argiolas does a D2 km-scale fold with overturned limb develop, the Monte Narba antiform (*figure 5*, *figure 9*) responsible for the vertical attitude of bedding and thrust planes of the imbricate zone S of Muravera. No white mica recrystallization occured, and cleavage development was restricted to the inner parts of folds.

The D2 deformation also affected the Gerrei, Meana Sardo, Castello Medusa-Riu Gruppa and Barbagia units. Whereas D1' has been attributed to continental collision and crustal shortening, D2 folding is interpreted as late- and post-collisional deformation, together with low angle normal faulting and tectonic exhumation [2]. The tectonic significance of D2 folds cannot be discussed in the Sarrabus unit, because clear overprinting relationships between D2 folding and low-angle normal faults are missing.

Later folding with NE-SW oriented fold axes (D3 phase of Carmignani and Pertusati [9]), is recognised but has no appreciable effects on the Sarrabus unit.

3.4 Late Hercynian faulting

Late, high angle normal faulting cuts the D1' and D2 folds in the Sarrabus unit. Two fault systems can be distinguished: E-W striking normal faults and N-S striking faults. The relationships between these two fault systems are still a matter of debate.

The Bruncu Istrias fault, a major tectonic lineament that can be followed for about 12 km between Genn'Argiolas and Monte Genis, belongs to the E-W system (*figure 4*). It is a vertical to steeply south-dipping normal fault cut by dykes associated with Late Carboniferous granite emplacement.

The N-S striking fault set (Bruncu Molentino fault, etc.) is of Hercynian age as is indicated by dykes which intruded along it. A later (Tertiary) reactivation occurred along the Gennarella fault, where a Pliocene-Quaternary basalt neck is intruded [38]. Movements along faults are limited to slips of hundreds of metres.

4. W-Directed tectonics in SE Sardinia: discussion and implications for nappe correlations

The area north east of San Vito, immediately below the Villasalto thrust, is well suited to discussion of the relative nappe relationships and kinematics of the Sarra-

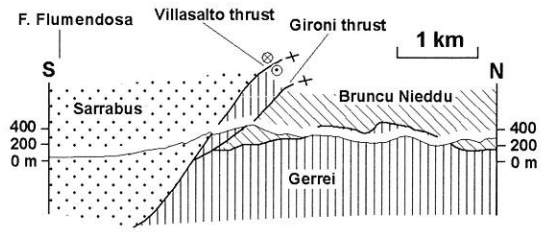


Figure 12. Sketch profile showing relative relationships between the Gerrei, Bruncu Nieddu (=Meana Sardo unit) and the Sarrabus unit, north-east of San Vito. See *figure 4* for profile location.

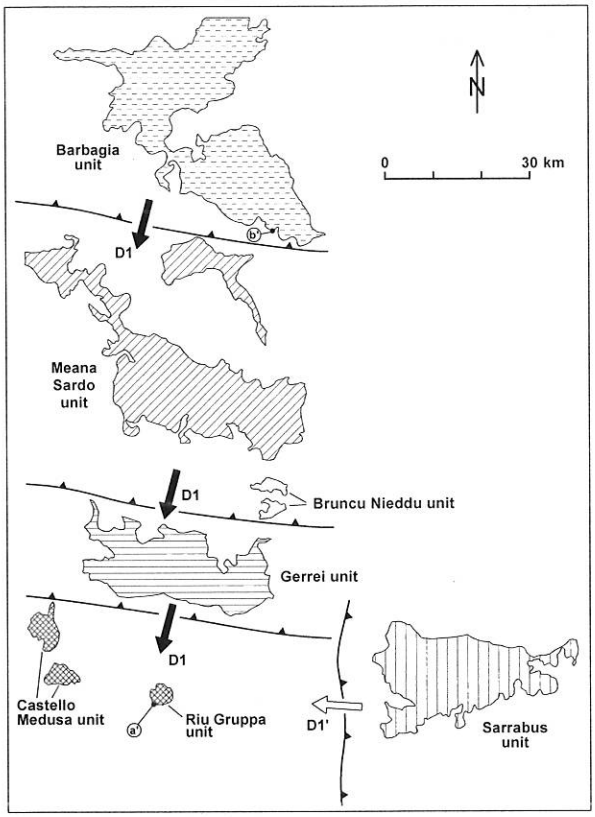


Figure 13. Pre-Carboniferous palinspastic reconstruction for the basement units of southeastern Sardinia. Recontruction based on *figure 1*; arrows give mean transport direction for D1 and D1'. No internal deformation in tectonic units is taken into account. a', b' are points used for shortening estimation (see *figure 1*)

bus, the Gerrei and the Meana Sardo units. In the whole of southeastern Sardinia the Meana Sardo unit overlies the Gerrei unit (*figure 1*). Only north east of San Vito (*figures 4* and *12*) tectonic slivers of the Gerrei unit lie below the Villasalto thrust and above the Gironi thrust, between the Sarrabus unit and the Bruncu Nieddu unit. As pointed out by Gattiglio and Oggiano [22], the Bruncu Nieddu unit is directly correlated with the Meana Sardo unit. Therefore the Gerrei unit in this area is in a higher position than the Meana Sardo unit. Due to poor outcrop conditions, no reliable shear sense indicators were found along the Gironi thrust (*figure 4*), nor in the highly sheared slivers of the overlying Gerrei unit. Cataclasites and tectonic slivers immediately below the Villasalto thrust are made up of rocks of the Gerrei unit, and occur between Villasalto and San Vito [3, 9]. We therefore interpret these occurrences above the Meana Sardo unit in the area north east of San Vito, in the same way: they are linked with movements along the Villasalto thrust and therefore contemporaneous with the emplacement of the Sarrabus unit.

Emplacement of rocks of the Gerrei unit on the Meana Sardo unit occurs where west-thrusting of the Sarrabus unit, with tectonic slivers of the Gerrei unit below, postdates south-directed emplacement of the Meana Sardo above the Gerrei nappe. The Villasalto thrust must therefore cut across a previously formed nappe stack, with the Meana Sardo unit already juxtaposed on the Gerrei unit.

This deformation sequence is supported by the observation that ubiquitous deformation features linked with N-S shortening well developed in the tectonic units north of the Villasalto thrust such as pervasive foliation, NNE-SSW stretching lineations, greenschist facies quartz-mylonites and outcrop-scale isoclinal folds, are not present in the Sarrabus unit. The Sarrabus unit must have been emplaced at a shallower crustal level, shortly after the D1 deformation of the lower units and before late D1 deformation that affected the entire nappe stack (*figure 2b*).

Based on the above observations, the Sarrabus unit is the uppermost tectonic unit in the Hercynian nappe stack of southeastern Sardinia and cannot be correlated with any of the tectonic units outcropping north of the Flumendosa antiform. The Sarrabus unit must therefore be located east of the Gerrei and Castello Medusa-Riu Gruppa unit in the Hercynian paleogeography (*figure 13*).

An assessment of the N-S shortening during D1 deformation must not include the Sarrabus unit. A comparison of the relative positions of points (a) and (b) in *figure 1* and the same points (a') and (b') in the reconstruction of *figure 13* indicates about 80 km shortening during SSW-thrusting. D1' westward transport of the Sarrabus unit cannot be constrained due to the Tertiary cover of the Campidano graben, but it may even be larger if one assumes that the Arburese unit (*figure 1*) is the westward extension of the Sarrabus unit, west of the Campidano graben [3, 39, 40].

A smooth transition in D1 fold axes orientation is assumed by Carmignani et al. [13] in the Hercynian basement east of the Campidano graben, from central to southern Sardinia. They recognised that NW-SE striking fold axes in central Sardinia progressively become N-S striking fold axes in southern Sardinia. Based on our field work in the Sarrabus, Gerrei and Meana Sardo units, we do not recognise progressive rotation in fold axis orientation, but a sudden change in shortening direction from NNE-SSW below the Villasalto thrust (D1 shortening) to E-W in the Sarrabus unit (D1' shortening) (*figure 14*).

In the Iglesiente area N-S shortening, exposed in open upright E-W oriented folds, was followed by E-W shortening [3, 6, 8, 41]. Fold interference produced km-scale "type 1" superposition geometry [42]. The transport direction during E-W shortening is "top-to-the-west", as inferred by facing direction of folds and thrust geometry (see profiles in [3]). If the commonly assumed correlation between the Arburese and Sarrabus units can be

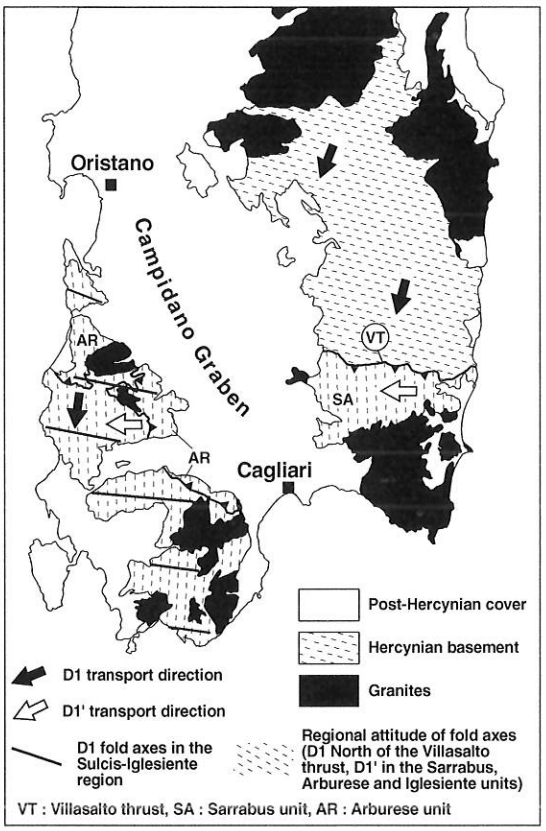


Figure 14. Fold axes orientation and transport direction in the Hercynian basement of central-southern Sardinia (after Carmignani et al. [13] modified). The Villasalto thrust separates northern tectonic units with only D1 deformation and is affected by south-thrusting from the Sarrabus unit, with only west-directed D1' deformation.

justified, the uppermost tectonic unit in the Iglesiente area also moved westward. The developed E-W oriented stretching lineations in the northern Arburese unit [40] makes the hypothesis of a westward emplacement of the Arburese unit plausible. The deformation history of the Iglesiente-Sulcis area may therefore be similar to what we interpreted in southeastern Sardinia, east of the Campidano graben. We propose that the D1' deformation in the Sarrabus unit was contemporaneous with some of the deformation in the Sulcis-Iglesiente region, where it resulted in N-S striking, west-facing folds.

5. Conclusions

Widespread thrusting to the west and the development of west-facing folds occurred in the Sarrabus unit during the Early Carboniferous. Imbrication can be well documented in the upper tectonic levels of the Sarrabus unit, now outcropping SW of Muravera. This deformation occurred during west-directed overthrusting of higher tectonic units that are now eroded.

The Villasalto thrust represents a major tectonic boundary, separating the Gerrei and Meana sardo units with widespread D1 deformation (isoclinal folding and NNE-SSW stretching lineations) but no D1' deformation, from the Sarrabus unit with D1' deformation (open to close folds and E-W stretching lineations) and no evidence of D1 deformation. Along the west-directed Villasalto thrust the Sarrabus unit lies directly above the Gerrei nappe between San Vito and S. Andrea Frius. North-east of San Vito, the Sarrabus unit lies above the Meana Sardo unit (Bruncu Nieddu unit) with slivers of the Gerrei nappe in between. This requires that west-directed emplacement of the Sarrabus unit above the Gerrei and the Meana Sardo units followed the south-directed thrusting of the Meana Sardo unit onto the Gerrei unit. Before Hercynian deformation the Sarrabus unit was therefore located east of the Gerrei and Meana Sardo units and cannot be correlated with the Meana Sardo or the Barbagia units .

Acknowledgements

This work was supported by the Servizio Geologico d'Italia-Regione Sardegna program "CARG L. 67/88". We would like to thank L. Carmignani and A. Funedda for fruitful discussions during this study, and two anonymous reviewers for their critical and constructive comments.

References

[1] Arthaud F., Sauniac S., Une coupe synthétique à travers la chaîne varisque de Sardaigne. Commentaires sur l'évolution tectono-métamorphique, Bull. Soc. géol. France, 23 (1981) 535–539.

[2] Carmignani L., Carosi R., Di Pisa A., Gattiglio M., Musumeci G., Oggiano G., Pertusati P.C., The Hercynian chain in Sardinia (Italy), Geodinamica Acta 7 (1994) 31–47.

[3] Carmignani L., Cocozza T., Ghezzo C., Pertusati P.C., Ricci C.A., Guida alla Geologia del Paleozoico Sardo, Guide Reologiche Regionali, Società Geologica Italiana, Cagliari, (1982) 215 p.

[4] Carosi R., Pertusati P.C., Evoluzione strutturale delle unità tettoniche erciniche nella Sardegna centro-meridionale, Boll. Soc. Geol. It. 109 (1990) 325–335.

[5] Dessau G., Duchi G., Moretti A.,Oggiano G., Geologia della zona del Valico di Correboi (Sardegna centro-orientale), Rilevamento, tettonica e giacimenti minerari, Boll. Soc. Geol. It. 101 (1982) 497–522.

[6] Arthaud F., Un exemple de tectoniques superposées dans le Paleozoique de l'Iglesiente (Sardaigne), C. R. Soc. géol. France 9 (1963) 303–304.

[7] Arthaud F., Etude tectonique et microtectonique comparée de deux domaines Hercyniens: Les nappes de la Montagne Noire (France) et l'anticlinorium de l'Iglesiente (Sardaigne), Publications de l'Université des Sciences et Techniques du Languedoc - Série Géologie Structurale, Montpellier, 1 (1970) 175 p.

[8] Poll J.J.K., Zwart H.J., On the tectonics of the Sulcis area, S Sardinia. Geol. Mijnbouw, 43 (1964) 144–146.

[9] Carmignani L., Pertusati P.C., Analisi strutturale di un segmento della catena ercinica: il Gerrei (Sardegna sud-orientale), Boll. Soc. Geol. It. 96 (1977) 339–364.

[10] Barca S., Maxia M., Assetto stratigrafico e tettonico del Paleozoico del Sarrabus occidentale, in: L. Carmignani, T. Cocozza, C. Ghezzo, P.C. Pertusati and C.A. Ricci (Eds.) Guida alla Geologia del Paleozoico sardo, Società Geologica Italiana. Guide Geologiche Regionali, Cagliari, (1982) 87–93.

[11] Barca S., Carmignani L., Eltrudis A., Gattiglio M., Pala L., Relationship between foredeep deposits and Hercynian nappe building in southeastern Sardinia (Italy), in: L. Carmignani and F.P. Sassi (Eds)., Contributions to the Geology of Italy with Special Regard to the Paleozoic Basements. Siena, IGCP No. 276, NEWSLETTER, 5, (1992) 33–44.

[12] Carosi R., Musumeci G., Pertusati P.C., Differences in the structural evolution of tectonics units in central-southern Sardinia, Boll. Soc. Geol. It. 110 (1991) 543–551.

[13] Carmignani L., Cocozza T., Minzoni N., Pertusati P.C., Falde di ricoprimento erciniche nella Sardegna a Nord-Est del Campidano, Mem. Soc. Geol. It. 19 (1978) 501–510.

[14] Naud G., Tentative de synthèse sur l'évolution géodynamique de la Sardaigne antépermienne, Mem. Soc. Geol. It. 20 (1979) 85–96.

[15] Cappelli B., Carmignani L., Castorina F., Di Pisa A., Oggiano G., Petrini R., A Hercynian suture zone in Sardinia: geological and geochemical evidence, Geodinamica Acta, 5 (1992) 101–118.

[16] Matte P., La chaîne varisque parmi les chaînes paléozoïques péri atlantiques, modèle d'évolution et position des grands blocs continentaux au Permo-Carbonifère, Bull. Soc. géol. France 8 (1986) 9–24.

[17] Cocozza T., Il Permo-Carbonifero del Bacino di San Giorgio (Iglesiente, Sardegna Sud Occidentale), Mem. Soc. Geol. It. 6 (1967) 607–642.

[18] Del Moro A., Di Simplicio P., Ghezzo C., Guasparri G., Rita F., Sabatini G., Radiometric data and intrusive sequence in the Sardinian Batholith, N. Jb. Miner. Abh. 126 (1975) 28–44.

[19] Di Simplicio P., Ferrara G., Ghezzo C., Guasparri G., Pellizzer R., Ricci C.A., Rita F., Sabatini G., Il metamorfismo e il magmatismo paleozoico nella Sardegna, Rend. Soc. It. Min. Petr. 30 (1975) 979–1068.

[20] Ferrara G., Ricci C.A., Rita F., Isotopic ages and tectonometamorphic history of the metamorphic basement of northeastern Sardinia, Contr. Min. Petr. 68 (1978) 99–106.

[21] Olivieri R., Conodonti e zonatura del Devoniano superiore e riconoscimento di Carbonifero inferiore nei calcari di Corona Mizziu (Gerrei-Sardegna), Boll. Soc. Paleont. It. 8 (1969) 63–152.

[22] Gattiglio M., Oggiano G., L'unità tettonica di Bruncu Nieddu e i suoi rapporti con le unità della Sardegna sud-orientale, Boll. Soc. Geol. It. 109 (1990) 547–555.

[23] Carmignani L., Conti P., Barca S., Cerbai N., Eltrudis A., Funedda A., Oggiano G., Patta E.D., Note Illustrative della Carta geologica d'Italia 1:50.000 "Foglio 549 - Muravera", Servizio Geologico d'Italia, Roma, (1997) in press.

[24] Barca S., Phénomènes de resédimentation et flysch hercynien à faciès Culm dans le "synclinal du Sarabus" (SE de la Sardaigne, Italie), C. R. Acad. Sci. Paris, 313 (1991) 1051–1057.

[25] Barca S., Di Gregorio F., La successione ordoviciano-siluriana inferiore nel Sarrabus (Sardegna sud-orientale), Mem. Soc. Geol. It. 20 (1979) 189–202.

[26] Calvino F., Lineamenti strutturali del Sarrabus-Gerrei (Sardegna sud-orientale), Boll. Serv. Geol. d'It. 81 (1959) 489–556.

[27] Maxia M., Segnalazioni di potenti successioni carbonifere marine nella Sardegna meridionale, Rend. Soc. Geol. It. 6 (1983) 21–24.

[28] Fontana D., Gelmini R., Lombardi G., Le successioni sedimentarie e vulcaniche carbonifere e permotriassiche della Sardegna, in: L. Carmignani, T. Cocozza, C. Ghezzo, P.C. Pertusati and C.A. Ricci (Eds.) Guida alla Geologia del Paleozoico Sardo, Società Geologica Italiana - Guide Geologiche Regionali, Cagliari, (1982) 183–192.

[29] Pittau Demelia P., Del Rio M., Acritarchi e loro significato stratigrafico nelle successioni paleozoiche della Sardegna, in: L. Carmignani, T. Cocozza, C. Ghezzo, P.C. Pertusati and C.A. Ricci (Eds.) Guida alla Geologia del Paleozoico Sardo, Società Geologica Italiana, Guide Geologiche Regionali (1982) 33–35.

[30] Gandin A., Depositional and paleogeographic evolution of the Cambrian in South-West Sardinia, I.G.C.P. No. 5 Newsletter 7 (1987) 151–165.

[31] Maxia M., Ricostruzione strutturale del tratto di catena ercinica sarda compresa nell'area tra il Sarrabus centro meridionale e il Gerrei. Evoluzione stratigrafica, tettonica, metamorfica e magmatica del Paleozoico italiano, Siena, 13–14 Dicembre 1985 92–93.

[32] Franceschelli M., Gattiglio M., Pannuti F., Fadda S., Illite crystallinity in pelitic rocks from the external and nappe zone of the Hercynian chain of Sardinia (Italy), in: L. Carmignani and F.P. Sassi (Eds.) Contributions to the Geology of Italy with Special Regard to the Paleozoic Basements, Siena, IGCP No. 276, NEWSLETTER 5 (1992) 127–135.

[33] Bakos F., Garbarino C., Mazzella A., Valera R.G., Pani E., Mineral association in the Sarrabus, SE Sardinia, Italy, gold silver lode and its genetic relevance. In: E.A. Ladeira Ed. The Economics, Geology, Geochemistry and Genesis of Gold Deposits, Proceedings of the Symposium Brazil Gold '91, Belo Horizonte, (1991) 515–522.

[34] Cortecci G., Reyes E., Leone G.,Turi B., Sulfur, oxygen, carbon and strontium isotope geochemistry of the Sarrabus-Gerrei Mining District, southeastern Sardinia, Italy. Economic Geology 82 (1987) 1592–1610.

[35] Valera R., Genesi ed evoluzione delle mineralizzazioni del Sarrabus (Sardegna sud-orientale), Rend. Soc. It. Min. Petr. 30 (1974) 1081–1108.

[36] White S.H., Knipe R.J., Transformation- and reaction-enhanced ductility in rocks, J. geol. Soc. London 135 (1978) 513–516.

[37] Wintsch R.P., Christoffersen R., Kronenberg A.K., Fluid-rock reaction weakening of fault zones, J. Geoph. Res. 100 (1995) 13021–13032.

[38] Calvino F., I basalti di Riu Girone (Villaputzu): nuova manifestazione di magmatismo recente presso la costa orientale sarda, Ric. Sci. 35 (1965) 1218–1243.

[39] Barca S., Cocozza T., Del Rio M., Pittau Demelia P., Discovery of lower Ordovician Acritarchs in the "Postgotlandiano" sequence of southwestern Sardinia (Italy): age and tectonic implications, Boll. Soc. Geol. It. 100 (1981) 377–392.

[40] Mazzarini F., Pertusati P.C., Structural evolution of Northern Arburese (SW Sardinia), Boll. Soc. Geol. It. 110 (1991) 747–755.

[41] Dunnet D., Deformation in Paleozoic rocks of Iglesiente, SW Sardinia, PhD Thesis, University of London (1969).

[42] Ramsay J.G., Folding and Fracturing of Rocks, McGraw-Hill, New York (1967) 568 p.

[43] Carmignani L., Cocozza T., Ghezzo C., Pertusati P.C., Ricci C.A., Structural Model of the Hercynian Basement of Sardinia. 1:500.000, Stabilimento L. Salomone, CNR, Progetto Finalizzato Geodinamica, Roma (1987).

[44] Calvino F., Carta Geologica d'Italia, Foglio 227-Muravera, 1:100.000. Servizio Geologico d'Italia, Roma (1963).

[45] Barca S., Carmignani L., Maxia M., Oggiano G., Pertusati P.C., The geology of Sarrabus. Guide book to the Excursion on the Paleozoic Basement of Sardinia, IGCP project n. 5, Newsletter, special issue, Cagliari, (1986) 51–60.

[46] Checchi F., Duchi G., Rapporti tra tettonica ercinica e mineralizzazioni nel Sarrabus orientale (Sardegna), Atti Soc. Tosc. Sci. Nat. Mem. Ser. A 90 (1983) 111–140.