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Change of nappe transport direction during the Variscan collisional evolution of central-southern Sardinia (Italy)

P. Conti[a,*], L. Carmignani[a], A. Funedda[b]

[a]*Dipartimento di Scienze della Terra, Università di Siena, Via Laterina 8, 53100 Siena, Italy*
[b]*Istituto di Scienze Geologico-Mineralogiche, Università di Sassari, Via Angioj 10, 07100 Sassari, Italy*

Abstract

The collisional Variscan (Early Carboniferous) evolution of the greenschist facies metamorphic basement of Sardinia is characterized by three deformation phases and two 90° reorientations of shortening direction. During the first phase of deformation N–S shortening occurred, with south-facing isoclinal folding, south-directed nappe emplacement and mylonitization in central and southeastern Sardinia, and large-scale E–W striking upright folds in southwestern Sardinia. Emplacement of the Barbagia, Meana Sardo, Gerrei and Riu Gruppa units took place during this event. This deformation phase was followed by E–W shortening, with W-directed emplacement of the Sarrabus and Arburese units along the Villasalto thrust and upright to E-dipping large-scale N–S striking upright folds in southwestern Sardinia. During the third deformation event, the shortening direction again rotated 90°, and N–S shortening produced kilometer-scale antiforms and synforms, the most prominent features in the metamorphic basement of Sardinia. The limbs of the kilometer-scale antiforms and synforms are vertically shortened during gravitational collapse, with contemporaneous faulting and conjugate shear zone development. Presence of large-scale E–W oriented antiforms was therefore critical for the formation of late Variscan extensional features, such as E–W striking, low-angle normal faulting.

Keywords: tectonics; Sardinia; Variscan deformation; polyphase deformation

1. Introduction

In Sardinia, the most continuous outcrops of Paleozoic rocks deformed during the Variscan orogeny are found in the central, southeastern and southwestern part of the island (Fig. 1). In each one of these regions a different tectonic evolution is documented during the Early Carboniferous collisional phases of Variscan deformation.

Earlier studies pointed out that overall S-directed transport is recognized as the most important direction of nappe emplacement during the Variscan deformation of central Sardinia. Neverthless, W-directed nappe transport is recognized in southeastern Sardinia instead. The whole nappe stack of central and southeastern Sardinia was subsequently refolded by E–W kilometer-scale antiforms and synforms. In southwestern Sardinia, a single shortening direction did not predominate during collisional tectonics, and the area is considered one of the best exposed examples of dome and basin structures, originating by interference between N–S and E–W shortening (Arthaud, 1963; Poll and Zwart, 1964; Carmignani et al., 1982).

Some questions still remain open in unraveling the Variscan evolution of central-southern Sardinia, namely: (a) why predominant S-directed shortening

* Corresponding author. Tel.: +39-781-75176; fax: +39-577-263880.
E-mail address: conti@unisi.it (P. Conti).

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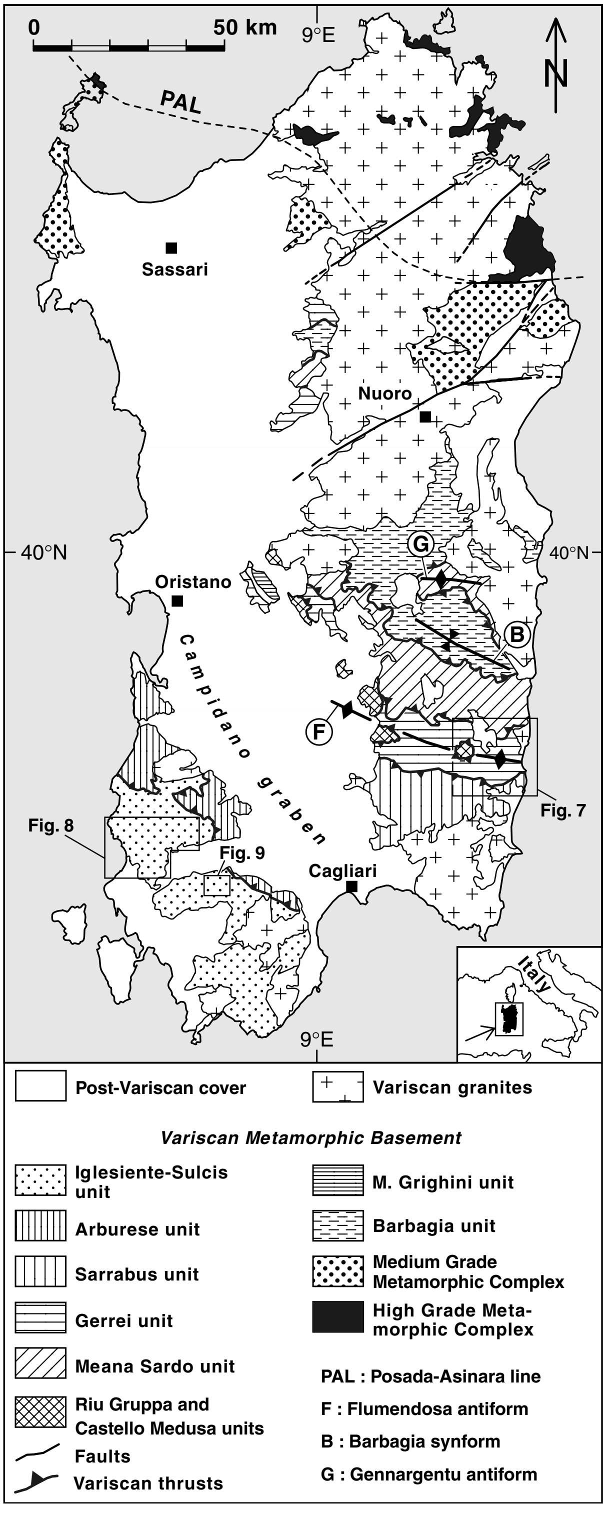

Fig. 1. Tectonic map of the Variscan basement of Sardinia.

is recognized only in central Sardinia and not in southern Sardinia; (b) why westward nappe transport is reported only in southern Sardinia and not in central Sardinia; (c) why two shortening directions are reported only in southwestern Sardinia (Iglesiente-Sulcis area) and not elsewhere; (d) why post-collisional antiformal structures bounded by low-angle normal faults are developed only in central and southeastern Sardinia and not in southwestern Sardinia. To explain such different tectonic evolutions between southwestern Sardinia and central-southeastern Sardinia, in this paper we correlate deformation phases in southeast Sardinia with deformation events in southwest Sardinia. In this attempt, we first critically review the main tectonic features in all those areas described by earlier authors, and then we give account of new field work results that permit us to propose a single tectonic scenario for the collisional Variscan evolution of southern Sardinia and to explain the different tectonic evolution between southwestern and central-southeastern Sardinia. The role of collisional structures in localizing deformation during the late orogenic extension of this sector of the Variscan orogen is also discussed.

2. Geological setting

Collision between the northern Armorican and the southern Gondwana continents during the Early Carboniferous produced deformation in the Paleozoic basement of Sardinia (Matte, 1986, and cited references), with closure of oceanic domains whose remnants outcrop now in the northern part of the island along the Posada-Asinara line (Cappelli et al., 1992). Deformation and metamorphism in Sardinia increases from south to north, i.e. approaching the Posada-Asinara line. In the foreland area of southwestern Sardinia only non-metamorphosed to lower greenschist facies metamorphic rocks are exposed. East of the Tertiary Campidano graben, greenschist facies metamorphic rocks prevail (phyllites and schists), whereas amphibolite facies metamorphic rocks (gneisses), migmatites and eclogites crop out in the northern part of the island (Fig. 1).

Development of the nappe stack of central and southern Sardinia has been investigated over the last 20 years (Carmignani et al., 1978, 1982, 1994; Naud, 1979). The deepest tectonic unit is the Riu Gruppa-Castello Medusa unit (Fig. 2), above which lies the Gerrei unit overridden by the Meana Sardo unit, in turn overthrust by the Barbagia unit. All these tectonic units are emplaced with a top-to-the-S transport direction (Carmignani et al., 1978, 1994; Carosi et al., 1991). The Sarrabus unit is the southernmost tectonic unit of southeastern Sardinia, and lies above both the Gerrei and the Meana Sardo units. The Sarrabus unit finds its prolongation west of the Campidano graben in the Arburese unit, which overthrusts the Iglesiente-Sulcis units in southwestern Sardinia. The Sarrabus and Arburese units were emplaced with a top-to-the-W transport direction (Carmignani and Pertusati, 1977; Conti and Patta, 1998). After nappe emplacement, the nappe pile of central and southeastern Sardinia was refolded by kilometer-scale upright synforms and antiforms striking WNW–ESE, refolding older foliations and thrust planes. All these deformation events were followed by post-collisional extensional tectonics (Carmignani et al., 1994), with normal faulting and vertical shortening that led to recumbent folding, granite intrusion and later strike-slip tectonics. Those events are summarized in Fig. 3. The Mesozoic–Tertiary sequence non-conformably overlies the Variscan basement, and shows little or no evidence of Alpine deformation in central-southern Sardinia.

3. Nappe emplacement and deformation in central and southern Sardinia

3.1. Nappe emplacement in central Sardinia

We first discuss the tectonic evolution during Variscan collisional tectonics of the nappe stack outcropping in central Sardinia, i.e. the Riu Gruppa-Castello Medusa unit, the Gerrei unit, the Meana Sardo unit and the Barbagia unit (Fig. 1). These tectonic units were emplaced during the Early Carboniferous with a top-to-the-S sense of thrusting (Figs. 4(a) and 5(a)), as reported by many authors and well recognizable all over the area (Carmignani et al., 1978, 1982; Carosi et al., 1991). The lithostratigraphic succession in southeastern Sardinia is similar in all the tectonic units. It begins with Cambrian–Lower Ordovician metasandstones, phyllites and quartzites at the base, followed by metaconglomerates and metavolcanic

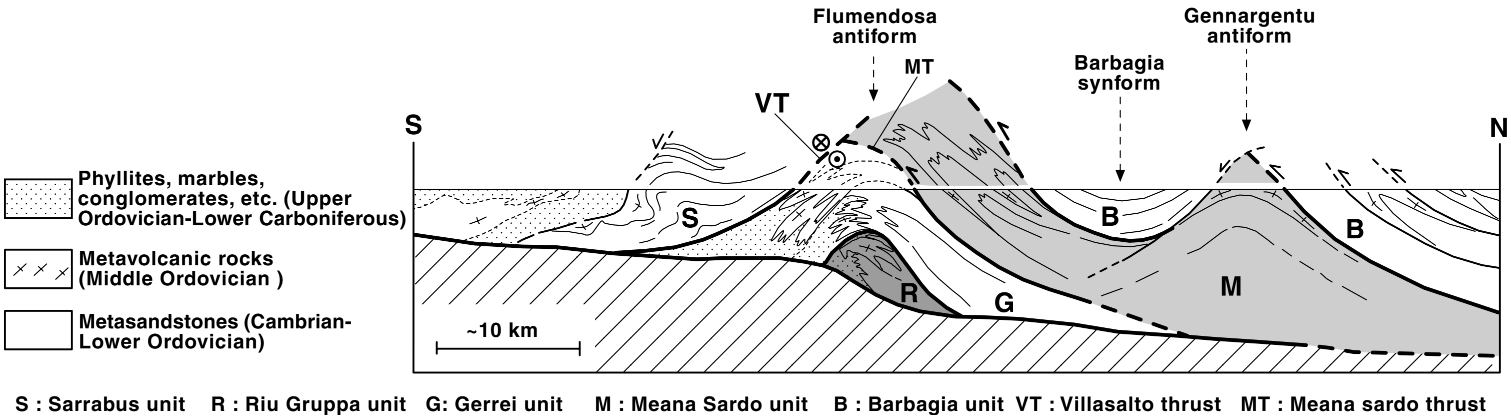

Fig. 2. Schematic cross-section in the Variscan basement of southeastern Sardinia.

This paper				Previous authors			
TECTONIC SETTING	*FEATURES*	*DEFORMATION PHASES*	*PHASE NAMES*	Conti & Patta, 1998	Carosi & Pertusati, 1990	Carmignani et al., 1978	time ↓
Crustal thickening	Early mylonitic deformation in the Barbagia, Meana Sardo and Riu Gruppa unit, folding and main regional schistosity in the Gerrei unit	D1: Early S-directed thrusting and folding	Gerrei phase	D1	D1	D1	
	Final emplacement, late mylonitic deformation, main foliation development in the Meana Sardo and Barbagia unit	D1: Main S-directed nappe emplacement	Meana phase		D2		
	Emplacement and main folding in the Sarrabus and Arburese units	D1: W-directed nappe emplacement	Sarrabus phase	D1'	D1		
	Large-scale upirght antiforms and synforms, crenulation cleavage	D1: Late stage N-S shortening	Flumendosa phase		D3	D2	
Tectonic exhumation	Normal faulting, NW-SE folds, crenulation cleavage	D2	Rio Gruppa phase	D2			
?	NE-SW folds, crenulation cleavage	D3		D3	D4	D3	

Fig. 3. Correlation of deformation events in the Variscan basement of central and southeastern Sardinia.

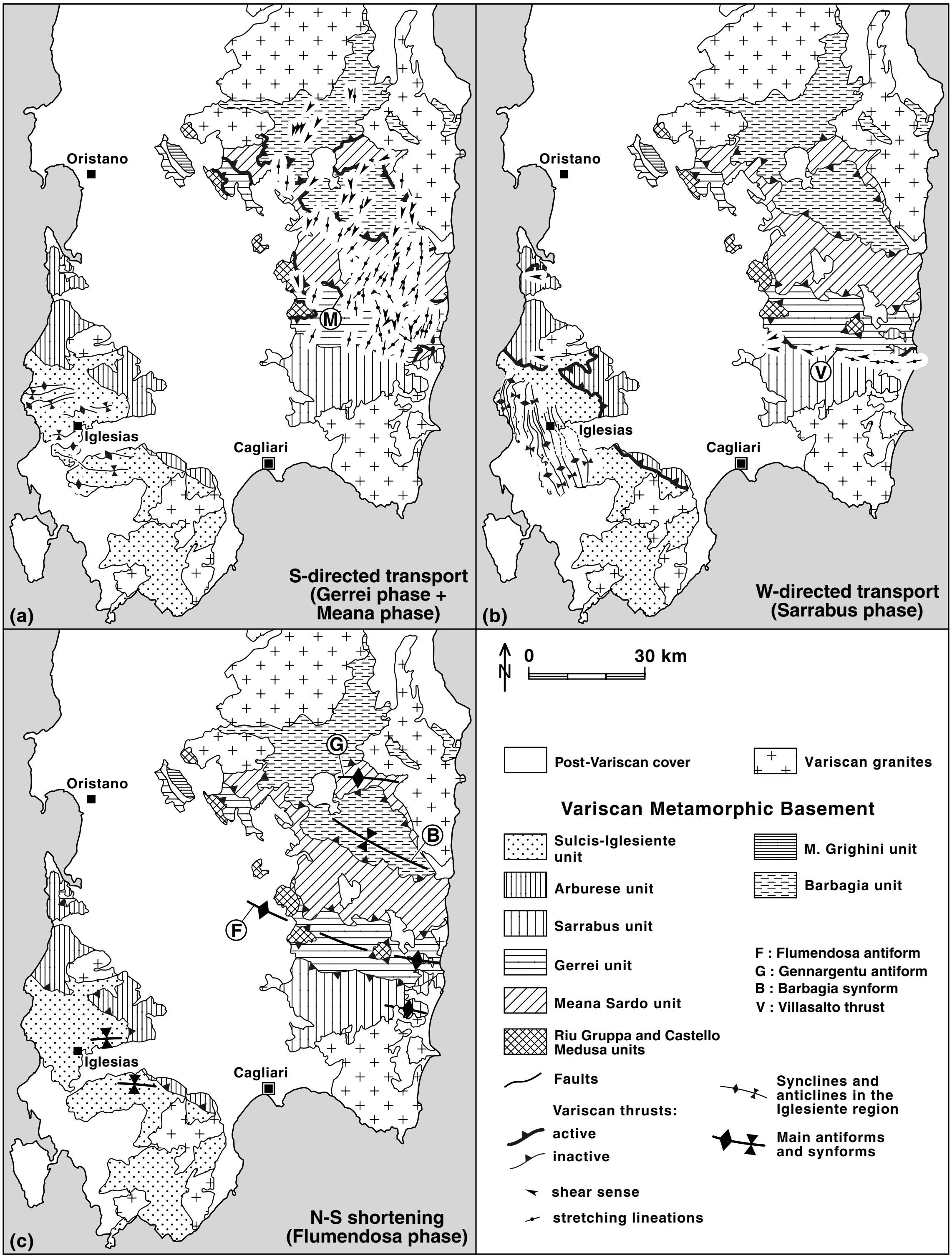

Fig. 4. Main tectonic features developed during crustal thickening deformation events in central and southern Sardinia. (a) Gerrei and Meana phase (S-directed nappe transport). (b) Sarrabus phase (W-directed nappe transport). (c) Flumendosa phase (N–S shortening).

rocks (rhyolites, andesites, metatuffites, metabasites, etc.) of Middle Ordovician age. The Upper Ordovician is characterized by meta-arkoses and metasiltstones passing into Silurian–Lower Devonian black shales, phyllites and marbles. Middle–Upper Devonian is represented by thickly bedded marbles, covered by Lower Carboniferous synorogenic flysch deposits (metaconglomerates, metasandstones, phyllites and quartzites with large olistolithic bodies).

The tectonic setting of the Barbagia and Meana Sardo units has been discussed by various authors (Minzoni, 1975; Carmignani et al., 1982; Dessau et al., 1982; Carosi and Pertusati, 1990; Gattiglio and Oggiano, 1990), all agreeing on the top-to-the-S sense of emplacement for both units, the presence of isoclinal folding under greenschist facies conditions, the development of a ubiquitous foliation and NNE–SSW oriented stretching lineations (Fig. 5(a)). Deformation is recognized to be polyphase, and two folding events are reported in both tectonic units by Dessau et al. (1982) and Carosi and Pertusati (1990) based on evidence that older folded foliations cut by the main regional foliation (Fig. 6(a)). Microstructural investigations (Conti et al., 1998) point to widespread mylonitic deformation in both tectonic units, not only to below main thrusts, accompanied by dynamic recrystallization (dislocation creep in quartz and calcite) under greenschist facies conditions. Isoclinal folds are often present, usually rootless and sheared along the foliation, at outcrop and thin section scale. We consider the Barbagia and the Meana Sardo units as a thick sequence of highly sheared rocks deformed under non-coaxial mylonitic conditions. Overprinting relationships between the main mylonitic foliation and older foliations (Fig. 6(a)) and the presence of refolded folds only testify to the polyphase character of the deformation and not the presence of two regionally distinct folding events. The main regional foliation in the Meana Sardo unit is parallel to the mylonitic foliation along the Meana Sardo thrust, the floor thrust that emplaced the Meana Sardo unit above the Gerrei unit. We infer therefore that main regional foliation in the Meana Sardo unit is developed contemporaneously with thrusting onto the Gerrei unit. Stretching lineations and sense of shear in mylonites along the Meana Sardo thrust show a top-to-the-S transport direction (Fig. 4(a)).

Tectonic setting of the underlying Gerrei unit is quite different. Here mylonitic deformation is confined to narrow zones beneath the main thrust planes, and the tectonic unit is characterized by kilometer-scale isoclinal folds facing southward (Fig. 7), with a penetrative axial plane foliation which is the main foliation recognizable in the field (Carmignani et al., 1982, 1994). Anticlinal and synclinal axial plane traces can be mapped for some kilometers in the field. Deformation again occurred under greenschist facies conditions. All previous authors have recognized these folding structures and have named this folding event "D1 phase" (Fig. 3). In order to avoid further misunderstanding, in this paper we refer to the phase that produced the kilometer-scale S-facing folds in Gerrei unit as the "Gerrei phase".

From the above discussion it is evident that a difference in internal deformation occurs between the strongly mylonitized Barbagia and Meana Sardo units and the regionally folded Gerrei unit. In order to investigate the relationships between nappe emplacement, mylonitic deformation and folding we studied in more detail the Gerrei unit outcropping below the Meana Sardo thrust (Fig. 7). In the Gerrei unit below the Meana Sardo unit and north of Riu Gruppa the foliation and axial planes of anticlines and synclines of the Gerrei phase are N-dipping; the same attitude as the Meana Sardo thrust (Fig. 7). In this area the stratigraphic contact between Middle Ordovician metaconglomerates and the younger metavolcanic rocks can be observed (Fig. 6(b)), and the following observations can be made. Two foliations are present in this outcrop: in the more competent coarse metaconglomerates, a steeply dipping foliation (Sa), parallel to the stratigraphic contact (S0) is the more evident surface, cut by a spaced, flat-lying crenulation cleavage (Sb). The metavolcanic rocks are less competent with respect to the metaconglomerates, and they also show two foliations: the flat-lying (Sb) is here the more penetrative surface and cuts an older steep foliation (Sa). We infer therefore that the flat-lying (Sb) is a foliation younger than the steep one (Sa), and that Sb penetratively developed only in the less competent metavolcanic rocks.

Field mapping has shown that Sb foliation becomes more penetrative approaching the Meana Sardo thrust and is parallel to the thrust plane. At the same time small-scale folds linked with Sb foliation development become tight to isoclinal in shape again

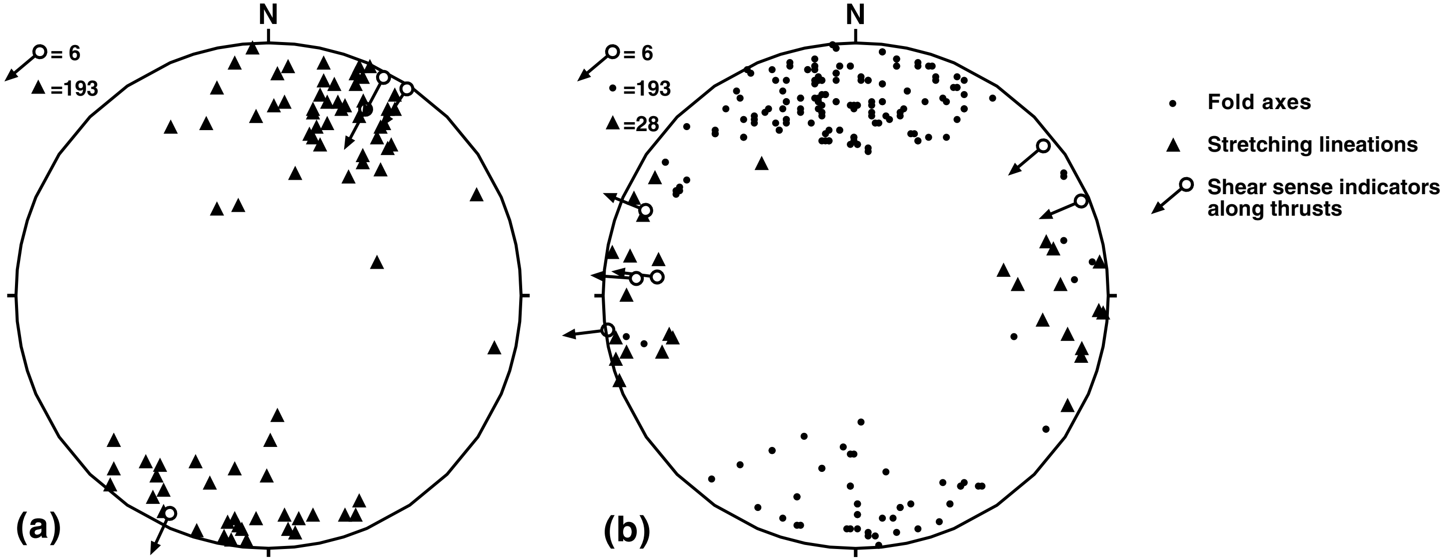

Fig. 5. Stereographic projections of structural data (equal area, lower-hemisphere plots) from central-southern Sardinia. (a) Data from the Barbagia, Meana Sardo, Gerrei and Riu Gruppa unit, showing stretching lineations and shear sense indicators developed during the Gerrei and Meana phase. (b) Data from the Arburese and Sarrabus unit, showing fold axes, stretching lineations and shear sense indicators developed during the Sarrabus phase.

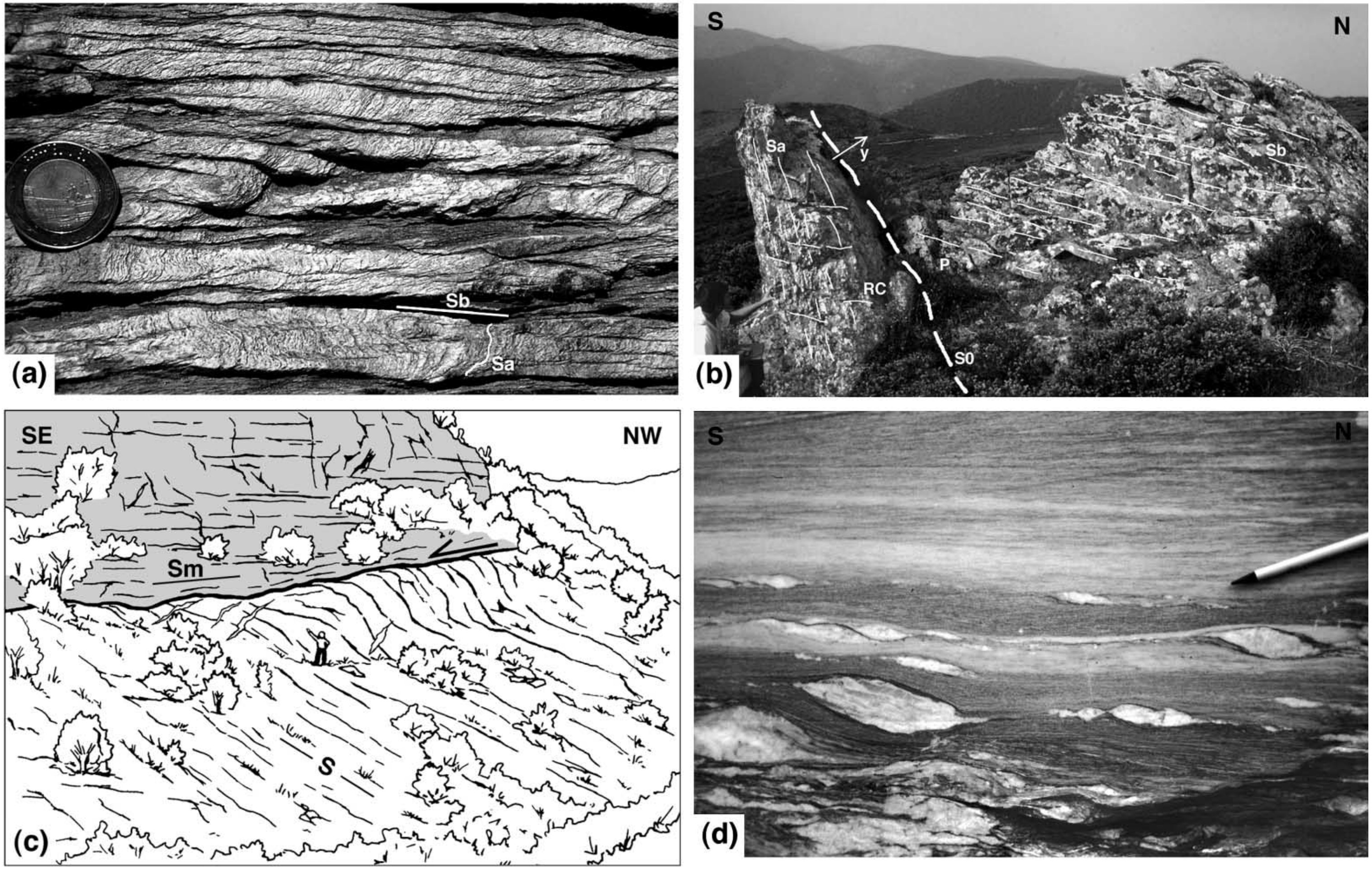

Fig. 6. (a) Polyphase folding and foliation development in the Barbagia unit. The foliation "Sa" is the main regional foliation, and cuts the earlier foliation "Sb". (b) Outcrop in the Gerrei unit (north of Arcu 'e Pesu, UTM coordinates 32SNJ38188168, see Fig. 7 for location) where the stratigraphic contact between Ordovician metaconglomerates ("Rio Ceraxa formation", RC) and the younger metavolcanic rocks ("Porfiroidi formation", P) is exposed. S0:bedding, Sa and Sb: foliations, y:younging direction. (c) Drawing after photograph of the normal fault marking the top of the Riu Gruppa unit, along the Riu Gruppa river (see Fig. 7 for outcrop location). A thick mylonite zone (in gray in the figure) developed during normal faulting, with a pervasive mylonitic foliation (Sm in the figure) at a high angle to the main regional foliation in the Riu Gruppa unit (S in the figure). (d) Shear sense indicators in mylonite (same outcrop as (c), UTM coordinates 32NJ37437546). Calcite nodule derived from deformed veins form σ-type porphyroclast system, asymmetry indicating sinistral (top-to-the-S) shear sense. Shear bands are also widely developed, again indicating top-to-the-S shearing.

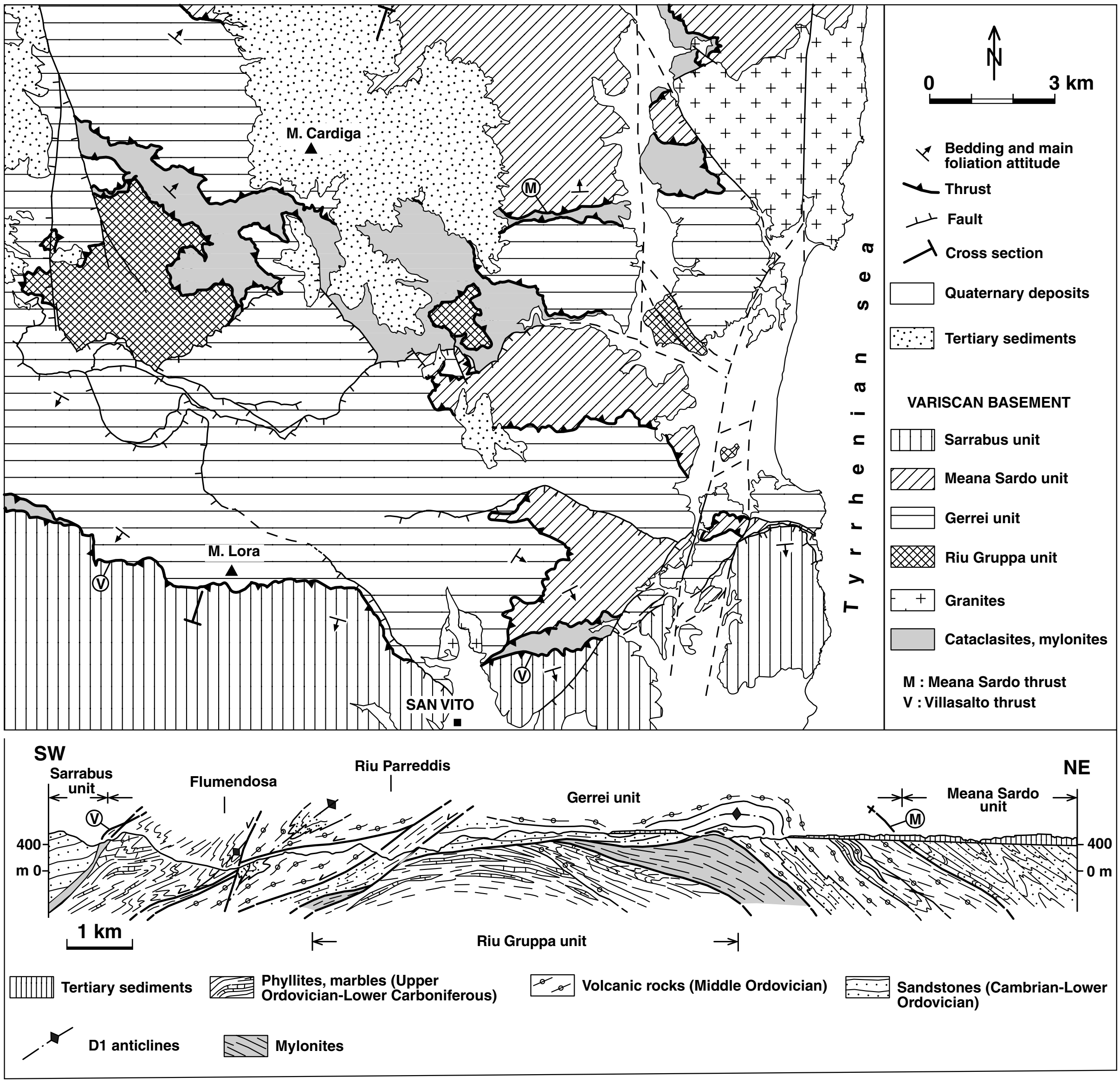

Fig. 7. Schematic tectonic map of the eastern termination of the Flumendosa antiform. See Fig. 1 for map location.

approaching the Meana Sardo thrust. Strongly non-cylindrical folds (sheath folds) are found below the thrust plane, with fold axes oriented parallel to the stretching lineations and the transport direction of the thrust. Sb foliation shows all the characteristics of a crenulation cleavage, with only small displacement along Sb surfaces. Shearing and recrystallization of quartz along Sb surfaces is only restricted to just below the thrust plane. We therefore infer that Sb is linked with S-directed emplacement of the Meana Sardo and Barbagia units.

The Sa foliation instead is the axial plane foliation of the large-scale isoclinal south-facing folds in the Gerrei unit. From the above observations it follows that isoclinal folding in the Gerrei unit (Gerrei phase) predates mylonitic deformation and S-directed final emplacement of the Barbagia and Meana Sardo units. We name the phase of late mylonitic deformation and final emplacement of the Barbagia and Meana Sardo units "Meana phase".

Folds and foliation developed during the Gerrei phase may still be preserved in the Barbagia and Meana Sardo units, but owing to strong mylonitization and polyphase evolution during the Meana phase, we could not unequivocally ascribe older foliation to the older regional folding event (Gerrei phase) rather than to a continuous deformation during the Meana phase. These difficulties are also enhanced by the lack of change in metamorphic conditions between the Gerrei and the Meana phases. In the Barbagia and Meana Sardo unit we therefore ascribe the main regional foliation to the Meana phase, and do not ascribe all the earlier foliations and folds to the Gerrei phase.

The Gerrei unit was thrust above the Riu Gruppa unit with a S-directed transport. During this deformation a mylonite zone up to 500 m thick developed, the Baccu Locci mylonite zone (Fig. 7). Microstructure and deformation mechanism evolution during deformation in the Baccu Locci mylonite zone are described by Conti et al. (1998) as internal deformation of the Riu Gruppa unit. During field work we were not able to definitively establish overprinting relationships between the main foliation in the Baccu Locci mylonites and the axial plane foliation of the kilometer-scale folds in the Gerrei unit, although the kilometer-scale isoclinal folds in the Gerrei unit nowhere refold the Baccu Locci mylonites. We therefore ascribe development of the Baccu Locci mylonites and resulting deformation in the underlying Riu Gruppa unit generically to the D1 S-directed deformation, without differentiating between Gerrei or Meana phase.

Following Gattiglio and Oggiano (1992), an overturned succession crops out in the Riu Gruppa unit, although strong D1 polyphase folding and foliation development (Carosi et al., 1990), and internal thrusting occur. The rocks in the Riu Gruppa unit just below the Baccu Locci mylonites (Cambrian sandstones and Ordovican volcanic rocks) show intense polyphase deformation with overprinting relationships between two foliations, with a flat-lying foliation cross-cutting a steeply dipping foliation, and thrusts generally parallel to the stratigraphic boundaries. The flat-lying foliation becomes more penetrative northward and is parallel to the main foliation of the Baccu Locci mylonites. This geometry resembles what we described before for the Gerrei unit below the Meana Sardo thrust, and accordingly we regard the internal deformation in this part of the Riu Gruppa unit to be related to the Gerrei and Meana phases. Mylonitic deformation linked with tectonic exhumation as reported by Gattiglio and Oggiano (1992) and Carmignani et al. (1994) is restricted to the southern part of the Riu Gruppa unit, in the footwalls of late Variscan normal faults.

3.2. Nappe emplacement in southern Sardinia

In southern Sardinia W of the Campidano graben the Arburese unit was emplaced above the Iglesiente-Sulcis unit, whereas E of the Campidano graben emplacement of the Sarrabus unit occurred (Fig. 1). Stratigraphic studies establish a direct correlation between the Arburese and the Sarrabus units (Barca et al., 1981, 1988; Pittau, 1984; Palmerini et al., 1985), and now the Arburese unit is generally regarded as the western prolongation of the Sarrabus unit.

Data on the tectonic setting of the Sarrabus unit are provided by Carmignani and Pertusati (1977) and by Barca and Maxia (1982). These authors recognized E–W shortening, local westward thrusting and large-scale folds with N–S striking axes, facing W. Carmignani and Pertusati (1977) also recognized the kinematics of the Villasalto thrust, a top-to-the-W thrust plane that places the Sarrabus unit onto the Gerrei unit. Later on Conti and Patta (1998) demonstrated that: (a) regional kilometer-scale thrusting affected the whole Sarrabus unit, with a top-to-the-W transport direction, (b) the Villasalto thrust is not the southernmost prolongation of the Meana thrust, and (c) the Sarrabus unit cannot be correlated with no tectonic units outcropping in central and southern Sardinia, except for the Arburese unit. Field work in the San Vito area (Fig. 7) indicates that the Sarrabus unit not only overthrust the Gerrei unit, but also the Meana Sardo unit, NE of San Vito. This means that W-directed thrusting of the Sarrabus unit follows S-directed emplacement of the Meana Sardo unit above the Gerrei unit (Gerrei phase and Meana phase). W-facing folds linked with W-thrusting are

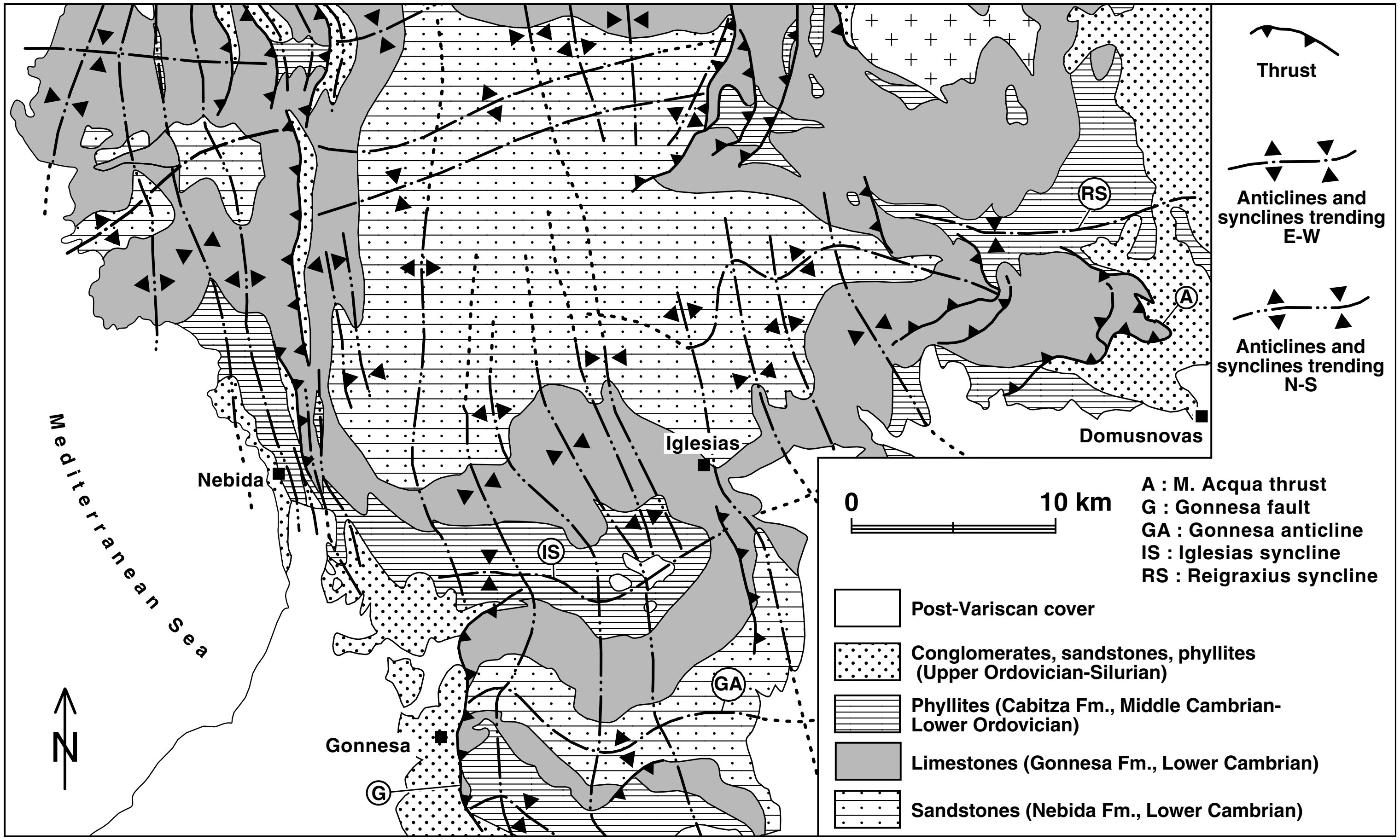

Fig. 8. Geological map of the Iglesias region (modified after Carmignani et al., 1982). See Fig. 1 for map location.

well exposed along the sea at Porto Tramatzu, just outside the area of the map in Fig. 7, and described in detail by Carmignani and Pertusati (1977). We name the tectonic phase of W-directed thrusting in southern Sardinia the "Sarrabus phase" (Fig. 3).

In the Arburese unit structural geological investigations are scarce and only deal with the northernmost part of the unit, south of Oristano (Fig. 4), whereas in a small tectonic window rocks of the Gerrei crop out beneath the Arburese unit (Mazzarini and Pertusati, 1991; Barca et al., 1992). These authors assert the similarity between the internal structure of the Arburese unit and the Sarrabus unit, with the same style of folding, internal local thrusting and the same metamorphic conditions during deformation. In the central and southern part of the Arburese unit, only a thick sequence of sandstones and phyllites crop out and recognition of large-scale folds and thrusts is more difficult. We investigate the base of the Arburese unit in order to infer transport direction during emplacement: owing to bad outcrop conditions shear sense indicators are scarce, but a penetrative foliation developed only near the floor thrust and parallel to the thrust plane. This foliation bears E–W striking stretching lineations; because foliation and lineations are not recognized away from the thrust plane, we interpret this foliation and the E–W stretching lineations to develop during nappe emplacement, following E–W transport. This inference about transport direction again supports the striking similarity between the Arburese and the Sarrabus units.

3.3. Deformation in southwestern Sardinia

In southwestern Sardinia, lower greenschist facies metamorphic rocks (Iglesiente-Sulcis unit) crop out beneath the Arburese unit (Fig. 1). The Iglesias area (Fig. 8) is well known for its Zn–Pb ore deposits and for excellent outcrop conditions, and for these reasons has been the object of intense geological investigation since the last century. Taricco (1912) and Novarese (1914) first recognized N–S and E–W oriented folds in the Iglesiente area, as regional-scale anticlines and synclines relate to these two directions of folding. Teichmüller (1931) first reported the occurrence of a thick conglomeratic succession ("Puddinga" Auct., Middle Ordovician) that rests with angular unconformity on all the older rocks. The conglomerates are considered moreover to rest unconformably on both limbs of the Iglesias syncline and the Gonnesa anticline (Fig. 8) From this it follows that the Iglesias syncline and the Gonnesa anticline are of pre-Middle Ordovician age, i.e. linked with Caledonian deformation. Most subsequent authors shared this interpretation (Vardabasso, 1956; Arthaud, 1963; Poll and Zwart, 1964; Poll, 1966; Dunnet, 1969; Arthaud, 1970; Carmignani et al., 1982), ascribing to the Caledonian deformation the E–W trending folds of the Iglesiente area. In this area it is also evident that post-Ordovician rocks suffered Variscan deformation and folding again along an E–W trend. No superposition of E–W Variscan folds on E–W Caledonian folds has been reported up to now, and for this reason it is usually assumed that the Variscan orogeny developed E–W folding in the post-Ordovician rocks and only tightened earlier E–W striking Caledonian folds in pre-Ordovician rocks.

Field work in the Iglesiente area led us to consider a fault contact, in agreement with Lüneburg and Lebit (1998), part of the basal contact of the Middle Ordovician conglomerates resting on the limbs of the Iglesias syncline and the Gonnesa anticline (Fig. 8). East of Gonnesa the contact is a steep reverse fault of Variscan age (the Gonnesa fault, Brusca and Dessau, 1968). It is not a local fault, but can be followed in the field for about 10 km toward the south. North of Domusnovas again the conglomeratic succession does not lie stratigraphically on both limbs of the Reigraxius syncline; the southern limb of the syncline is affected by thrusting (M. Acqua thrust). Again in this case we cannot demonstrate a Caledonian age for the large-scale E–W syncline. Whatever the age of the E–W oriented folding structures, all authors agree in considering these structures refolded by later N–S oriented folds, surely of Variscan age. Interference of large-scale upright E–W folds with upright N–S oriented folds led to the formation of "type 1 interference pattern" (Ramsay, 1967), with development of dome and basin structure. The development of N–S striking folds is also accompanied by development of N–S striking reverse faults dipping toward the E and the W (Carmignani et al., 1982; Carosi et al., 1992). We consider the kilometer-scale E–W trending anticlines and synclines of the Iglesias area of Variscan age, because direct evidence for a Caledonian age

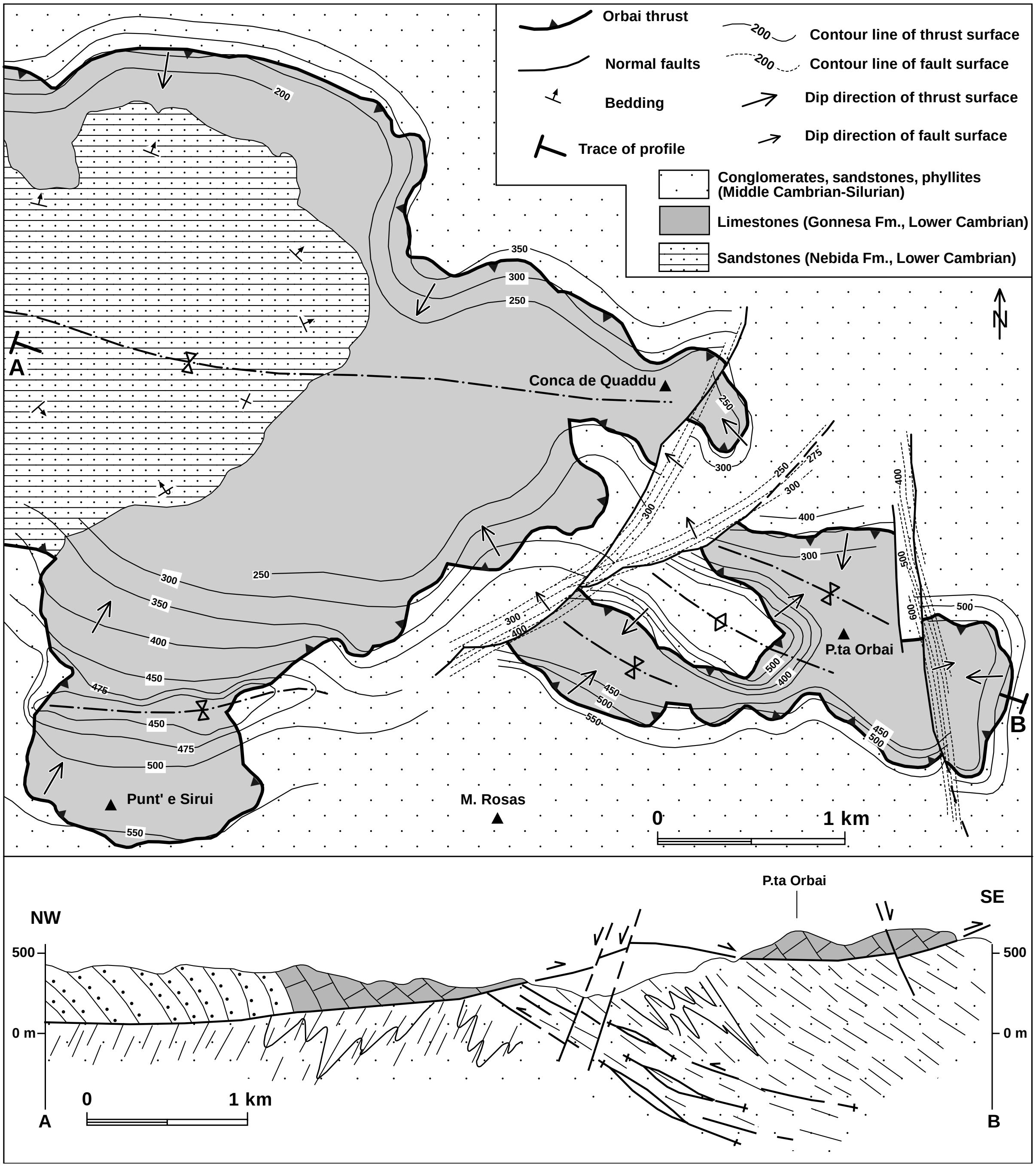

Fig. 9. Contour map of the Orbai thrust in southwestern Sardinia (see Fig. 1 for map location), refolded by large-scale E–W folds. Contour interval is 50 m, except where indicated.

of these structures is still missing and because of the similarity of the tectonic evolution of this area with central and southeastern Sardinia, where Variscan N–S shortening is followed by E–W shortening.

4. Change of transport direction during nappe emplacement

On the basis of the above discussion, it can be demonstrated that the Variscan basement of central and southern Sardinia suffered two stages of shortening and nappe emplacement during Early Carboniferous time. The first deformation event is characterized by N–S shortening, with a "top-to-the-S" nappe transport direction (Gerrei and Meana phases, Fig. 4(a)). This deformation is evidenced by isoclinal kilometer-scale S-facing folds in the Gerrei unit, by "top-to-the-S" shear sense indicators in the Barbagia unit and along the Meana thrust, by ubiquitous NNE–SSW stretching lineations in central Sardinia and by development of upright E–W striking folds in the Iglesias region.

After this deformation a 90° rotation in shortening direction occurred during the Early Carboniferous: after S-directed emplacement, nappe transport was toward the W. This is evidenced by "top-to-the-W" shear sense indicators along the Villasalto thrust, by E–W stretching lineation in the Sarrabus unit and along the floor thrust of the Arburese unit, by widespread W-facing folds in the Sarrabus unit and by N–S striking folds in the Iglesias area (Fig. 4(b)).

5. Renewed N–S shortening

Subsequent to W-directed nappe transport and crustal thickening that occurred in central and southern Sardinia, large-scale antiforms and synforms developed throughout the area, refolding earlier thrust planes, stretching lineations, isoclinal folds and related axial plane foliation. This folding is characterized by E–W to ESE–WNW striking upright folds, well developed in central Sardinia (Flumendosa antiform, Barbagia synform and Gennargentu antiform: Carmignani et al., 1994). The most striking feature is the kilometer-scale Flumendosa antiform (Figs. 1 and 4), and we therefore name this deformation event the "Flumendosa phase". Metamorphic grade is lower than during the earlier deformation events, and only a spaced crenulation cleavage develops in phyllites. No thrusting occurred during this phase, and shortening was less than in the previous deformations. Folds show vertical axial planes, and therefore no clear transport direction can be associated with this event. However, if we admit that the shortening direction had to be perpendicular to the trend of fold axes (no evidence of strike-slip tectonics has been found in the area during this phase), it had to be NNE–SSW oriented, about 90° rotated from the shortening direction we infer for the Sarrabus phase.

This deformation phase also produced antiforms and synforms in the Sarrabus unit (Conti and Patta, 1998) and in the Iglesiente-Sulcis unit (Fig. 4), where E–W oriented fold axes deform earlier N–S striking thrust planes. One of the best examples occurs in the M. Orbai area (Fig. 9). The M. Orbai thrust is a tectonic contact developed during E–W shortening that places Cambrian sandstones and limestones above Ordovician schists, cutting an E–W striking anticline and dipping to the W. In calcite mylonites along the thrust plane, E–W oriented stretching lineations are ubiquitous, associated with "top-to-the-E" shear sense indicators. The thrust plane is folded in a kilometer-scale open E–W syncline, the southern limb dipping north and the northern limb dipping south. The Flumendosa phase is therefore not restricted to central Sardinia, but affects all of central and southern Sardinia. It is important to notice that shortening during this phase again decreased from north to south. In the Barbagia, Meana Sardo and Gerrei units folds of this phase can be followed for several kilometers in the field, in some cases have overturned limbs (for instance near Villasalto) and typically are tighter folds with respect to the folds found in the Sarrabus and in the Iglesiente-Sulcis units. This deformation event marked the end of crustal shortening phases in Sardinia.

Large-scale features produced by the Flumendosa phase play a key role in localizing deformation during subsequent extensional tectonics (D2 phase, Fig. 3). Normal faults developed during tectonic exhumation are not widespread throughout the area, but are concentrated in the limbs of the main antiforms (Flumendosa antiform, Gennargentu antiform). As can be seen in Fig. 7, the normal faults dip from the hinge zone toward the limbs of the antiforms, leading to tectonic unroofing of the antiform culminations.

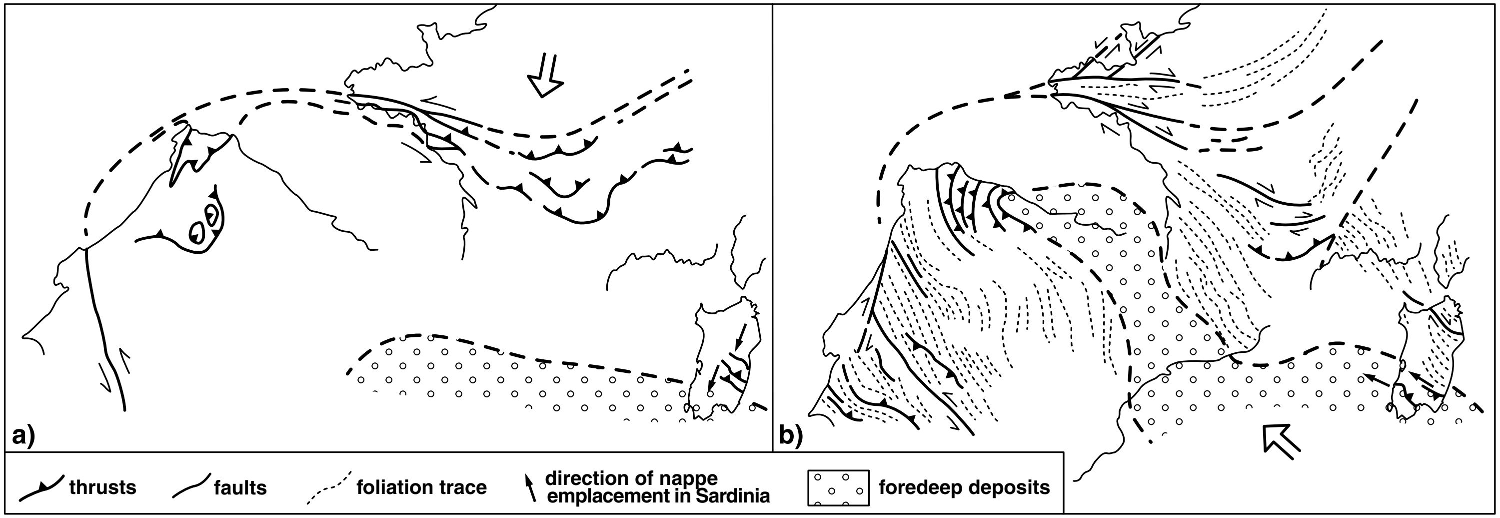

Fig. 10. Sketch illustrating direction of nappe emplacement in Sardinia during the evolution of the Ibero-Amorican arc (after Matte, 1986a; Brun and Burg, 1982, modified). (a) Early Variscan southward thrusting. (b) Westward Variscan indentation.

Because large-scale folds of the Flumendosa phase are found mostly in central and southeastern Sardinia (Gennargentu antiform, Barbagia synform and Flumendosa antiform, Fig. 1), kilometer-scale normal faults also occurred in this area and up to now have not been reported from southwestern Sardinia. One of the main normal faults crops out in the core of the Flumendosa antiform, and it is responsible for the uplift of the deeper tectonic unit in the nappe stack of central and southern Sardinia, the Riu Gruppa unit. This normal fault (Fig. 6(c)), directly places the uppermost tectonic levels of the Gerrei unit (schists and metasandstones) onto the lowermost levels of the Riu Gruppa unit (schists and marbles). In the area depicted in Fig. 7, the normal fault cuts schists and marbles of the lower Riu Gruppa unit and calcite mylonites developed along it. Below the normal fault, foliation in the Riu Gruppa unit is at a high angle to the mylonite boundary (Fig. 6(c)), and only in the vicinity of the mylonite zone is it rotated into parallelism with the shear zone boundary. Stretching lineations in the calcite mylonite are N–S oriented, and shear sense indicators (Fig. 6(d)) consistently indicate a "top-to-the-S" sense of shear. Crystal plasticity features associated with normal faulting are observed in calcite grains, but the studied calcite mylonites also bear scattered quartz grains. Quartz shows evidence only of dislocation glide (undulose extinction and deformation bands); this suggests (together with crystal plasticity in calcite) a temperature lower than 300°C during normal faulting and mylonite formation (Stipp et al., 1999).

6. Geodynamic significance

Discussion of the Variscan deformation phases of Sardinia in the framework of the geodynamic evolution of the south-European Variscan chain is complicated by the current isolated position of the Sardinia–Corsica block in the Mediterranean due to the Miocene drifting (Vigliotti and Langenheim, 1995, and bibliography). Restoring Sardinia in its pre-Permian position it comes to locate near Provence, we must therefore discuss the deformation history we recognized in Sardinia with the tectonic evolution of the Iberian peninsula and southern France. Previous authors have already pointed out the similarities between the migmatitic complex of northern Sardinia and the comparable high-grade metamorphic complex outcropping in the Maures (southern France), between the Iglesiente region and the Montagne Noire (Arthaud, 1970; Orsini, 1976; Arthaud and Matte, 1977; Ricci and Sabatini, 1978; Matte, 1986).

In the early stages of deformation an east–west oriented subduction zone is active in the south-European Variscides, with north–south convergence direction and northward underthrusting (Brun and Burg, 1982, Fig. 10(a)). At this time Sardinia is located in a more external position with respect to the collision zone and this can explain the different age of north–south shortening in the internal zone of France and Iberia (Devonian) with respect to Sardinia (Early Carboniferous). During this tectonic event southward nappe emplacement occurred in Sardinia (Gerrei and Meana phases). Tightening of the Ibero-Armorican arc during later Variscan deformation is related to westward motion of the Cantabrian indenter (Fig. 10(b)), leading to sinistral shearing in Iberia, dextral shearing in the Armorican peninsula and thrusting in the central part of the arc (Matte and Ribeiro, 1975; Brun and Burg, 1982; Ribeiro et al., 1995; Dias and Ribeiro, 1995). During this event westward nappe emplacement occurred in Sardinia (Sarrabus phase) and most likely strike-slip tectonics along east–west oriented faults (dextral shearing along the Posada-Asinara line in northern Sardinia). It is more difficult to explain the later N–S shortening during the Flumendosa phase. This could be linked with local transpressions during westward shearing producing shortening transverse to the regional transport direction (Ribeiro et al., 1995).

7. Conclusions

New data are presented to better constrain the tectonic evolution of central and southern Sardinia during the Variscan orogeny (Early Carboniferous). N–S shortening (already reported by earlier authors) predominated during earlier phases of deformation (Gerrei phase and Meana phase), producing polyphase isoclinal folding, nappe emplacement and mylonitization in central and southeastern Sardinia, and large-scale E–W striking upright folding in southwestern Sardinia. The Barbagia unit, Meana Sardo unit, Gerrei unit and the Riu Gruppa unit were emplaced during this N–S shortening. We recognize that these deformation events were followed by E–W shortening (Sarrabus phase), recognizable only in the higher levels of the Variscan nappe stack, now cropping out in southern Sardinia. During this phase, W-directed emplacement of the Sarrabus and Arburese unit occurred. Emplacement of the Sarrabus unit took place along the Villasalto thrust, cutting thrusts and foliations of the earlier phases, placing the Sarrabus unit above both the Gerrei and Meana Sardo units. In southwestern Sardinia, E–W shortening produced large-scale, upright to steeply inclined folds, with N–S oriented fold axes, and reverse faults.

Field investigations point to a deformation event (Flumendosa phase) that again produced N–S shortening. Shortening was significantly less than during the earlier phases, and only large-scale antiforms and synforms developed. The most important antiform in southeastern Sardinia is the Flumendosa antiform, which developed just north of the Villasalto thrust, producing an asymmetry in the nappe distribution with respect to the Flumendosa antiform hinge zone: north of the Flumendosa antiform, the Gerrei unit is overlain by the Meana Sardo and the Barbagia units, whereas south of the Flumendosa antiform, the Gerrei unit is mostly overlain by the Sarrabus unit. In the limbs of the kilometer-scale antiforms originated during later N–S shortening developed normal faults. From this it follows that formation of large-scale E–W oriented antiforms were crucial for the formation of late Variscan, E–W striking, low-angle normal faults. These features are well recognized in central and southeastern Sardinia but are missing in southwestern Sardinia, where the late crustal thickening phase did not develop large antiforms and synforms.

Deformation events recognized in Sardinia are discussed in the framework of the tectonic evolution of the Ibero-Armorican arc. The Gerrei and Meana phases show shortening direction perpendicular to the Variscan suture zone and are linked with collisional evolution of the Ibero-Armorican arc, the Sarrabus and Flumendosa phases developed during westward shearing of the Cantabrian indenter.

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