AGU PUBLICATIONS

Tectonics

RESEARCH ARTICLE

10.1002/2014TC003759

Key Points:

- The presence of a crustal discontinuity in western Sicily
- High-resolution seismic tomographic models
- Oblique convergence in the Maghrebian chain

Supporting Information:

- Table S1

Correspondence to:
G. Zarcone,
giuseppe.zarcone@unipa.it

Citation:
Di Stefano, P., R. Favara, D. Luzio, P. Renda, M. S. Cacciatore, M. Calò, G. Napoli, L. Parisi, S. Todaro, and G. Zarcone (2015), A regional-scale discontinuity in western Sicily revealed by a multidisciplinary approach: A new piece for understanding the geodynamic puzzle of the southern Mediterranean, *Tectonics*, *34*, 2067–2085, doi:10.1002/2014TC003759.

Received 31 OCT 2014
Accepted 1 SEP 2015
Accepted article online 4 SEP 2015
Published online 3 OCT 2015

A regional-scale discontinuity in western Sicily revealed by a multidisciplinary approach: A new piece for understanding the geodynamic puzzle of the southern Mediterranean

Pietro Di Stefano[1,2], Rocco Favara[2], Dario Luzio[1,2], Pietro Renda[1,2], Maria Simona Cacciatore[1], Marco Calò[3,4], Giuseppe Napoli[1], Laura Parisi[5], Simona Todaro[1], and Giuseppe Zarcone[1]

[1]Dipartimento di Scienze della Terra e del Mare, Università di Palermo, Palermo, Italy, [2]Sezione di Palermo, Istituto Nazionale di Geofisica e Vulcanologia, Palermo, Italy, [3]Berkeley Seismological Laboratory, Berkeley, California, USA, [4]Now at Instituto de Geofísica, Universidad Nacional Autonoma de Mexico, Mexico City, Mexico, [5]School of Environmental Sciences, University of East Anglia, Norwich, UK

Abstract The results of an integrated stratigraphic, structural, geophysical, and geochemical study reveal the presence of a crustal discontinuity in western Sicily that, at present, runs roughly N-S along a band from San Vito Lo Capo to Sciacca. The boundary between the two zones of this discontinuity is nearly orthogonal to the main thrust propagation of the Sicilian thrust-and-fold belt. The different Permian to Tertiary sedimentary evolution recorded by the two zones appears related to this discontinuity, with thick carbonate platforms in the western sector facing deepwater successions in the eastern one. The presence of Upper Triassic reefs, huge megabreccia bodies, and widespread submarine volcanisms along the transition zone suggests the presence of a long-lasting weakness zone. This zone has been reactivated episodically as transpressional and/or transtensional faults in relation to the different geodynamic stress acting in central Mediterranean area in different epochs. We speculate that this transition zone has represented a segment of the passive margin of the Ionian Tethys. During the Maghrebian convergence a different style of deformation has affected the two sectors floored by different sedimentary multilayers. The orthogonal-to-oblique differential convergence between the two sectors has resulted in right-lateral transpressional motions, leading to oblique thrusting of deepwater-derived thrusts onto platform-derived thrusts associated with clockwise rotations. The oblique convergence is still ongoing as demonstrated by the seismicity of the area, by the geothermal field with high mantle-derived helium fluxes and by the GPS measurements collected by different authors.

1. Introduction

The interplay between crustal discontinuities, thickness, and composition of sedimentary cover together with the presence of paleotectonic structures and their orientation is of crucial importance to determine along strike variations in orogenic wedges [e.g., *Mitra*, 1997; *Gessner et al.*, 2013].

In Sicily (southern Italy) several authors have highlighted how the strong difference of thickness between thick shelf carbonates and thinner deepwater successions could have triggered, in the western Sicilian-Maghrebian chain, oblique thrusting, lateral escapes, and rotations during the tectonic stacking [e.g., *Monaco et al.*, 2000; *Speranza et al.*, 2000; *Tavarnelli et al.*, 2004].

According to *Nigro and Renda* [2002], the emplacement of thin deepwater-derived thrusts onto shelf carbonates with an overall oblique/lateral ramp geometry (as observed in the San Vito Lo Capo Peninsula and in the Sciacca-Monti Sicani zone) can be explained by the presence of a Mesozoic-Cenozoic indented fault-controlled margin of the Hyblean-Pelagian Block.

According to *Casero and Roure* [1994], in western Sicily a NW-SE regional trending shear zone (Segesta Fault) runs across the Sicilian fold-and-thrust belt (SFTB), from San Vito Lo Capo to the Sciacca area. The authors consider the Segesta Fault to be a first-order crustal structure, as it is observed in seismic lines offshore of Sciacca. However, the field evidence of this strike-slip fault is weak.

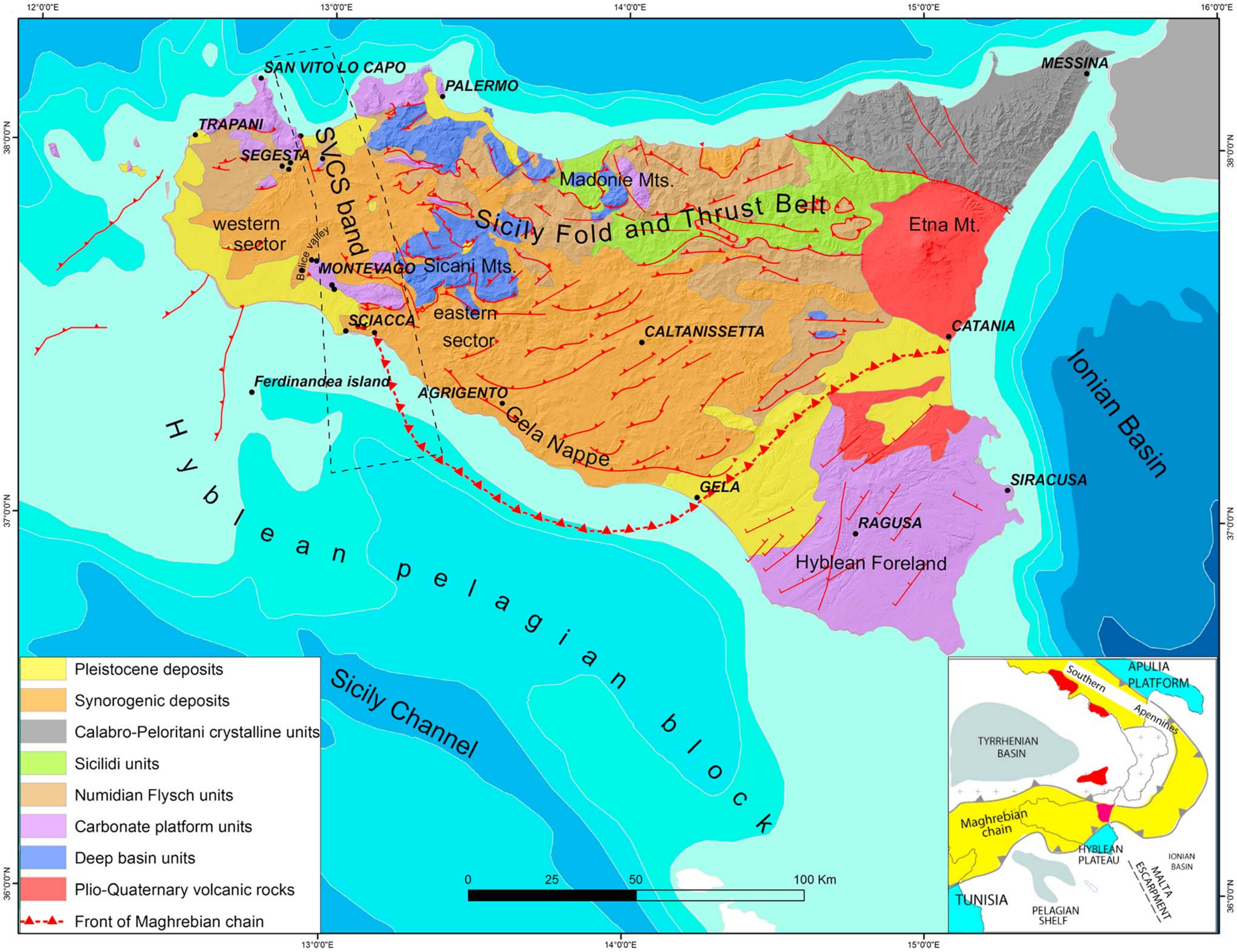

Figure 1. Structural sketch of Sicily showing the present-day front of the Maghrebian chain, the NNW-SSE trending SVCS band, and the western and eastern sectors with different style and amount of deformation.

The presence of such an important structural discontinuity in the Sciacca area and offshore is suggested by a sudden change of orientation of the main tectonic structures that makes it difficult to outline the front of the Maghrebian fold-and-thrust belt, which is otherwise well imaged, offshore from Agrigento.

The necessity to provide a reliable tectonic model of the San Vito Lo Capo-Sciacca band (SVCS) is dictated by three main geological aspects:

1. Geodynamic implication: the mechanism originating the tectonic structures of the area is still not fully understood;
2. Seismic hazard: the area was affected by the 1968 Belice earthquake ($M_w = 5.6$) whose source mechanism is poorly constrained by the seismic records;
3. Geothermal and hydrocarbon potential: geothermal fields and springs are well known along this band, in particular in the Castellammare area (Terme Segestane), in the Belice Valley (Montevago), and at Sciacca (Terme Selinuntine). Furthermore, after the negative results of an extensive drilling campaign during the 1960s a new interest has been recently refocused in this area.

In this paper we present recent multidisciplinary data collected along the SVCS that integrate stratigraphic and structural analyses with subsurface data acquired by geophysical and geochemical studies in order to evaluate the possible correlation between crustal variations and (paleo) tectonic structures. The aim is to tie the observed stratigraphic and structural features to a crustal anomaly and to define its role during the accretion of the Maghrebian chain and its present-day behavior.

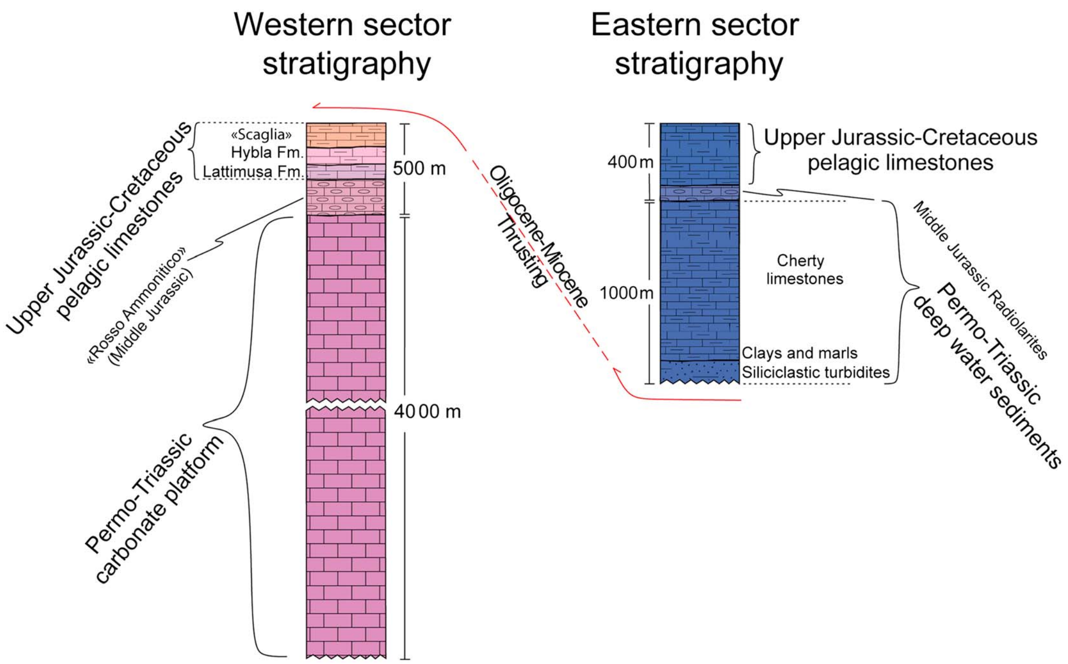

Figure 2. Stratigraphic columns showing the different stratigraphy and thickness of the sedimentary multilayer in the western and eastern sectors of the SVCS.

2. Geological Setting of the Western Sicily

The Sicilian mainland represents the emergent segment of the SFTB and extends from the Sardinia Channel to the Sicily Strait. The SFTB trends west-east across the island and consists of an Africa-verging thrust wedge (Figure 1). The preorogenic sequences mostly consist of Permian-Cenozoic carbonates and marls, in which the facies associations are typical of carbonate platforms, pelagic platforms, and deepwater basins (Figure 2). According to *Rosenbaum et al.* [2004] and *Zarcone et al.* [2010] the original sedimentary basins were located along the western termination of the Ionian Tethys. By late Oligocene time onward, these preorogenic sequences experienced contraction to form a thrust system. The outer zone of the SFTB consists of thin-skinned thrusts of mostly Tertiary terrigenous and evaporitic sediments known as the Gela Nappe [*Ogniben*, 1969; *Argnani*, 1989; *Lickorish et al.*, 1999].

The SVCS separates the western segment of the SFTB in two different sectors (Figures 1 and 2):

1. The western sector that is characterized by an imbricate fan of thick (up to 3–4 km) tectonic units made of Triassic-Lower Jurassic carbonate platform successions evolving to Rosso Ammonitico, Lower Cretaceous marls, and Scaglia-type sediments. The décollement zones are located in the evaporitic/marly horizons that occur in the Triassic shelf carbonates and/or in the Lower Cretaceous marly sediments. According to *Zarcone and Di Stefano* [2008] and *Zarcone et al.* [2010] these structural units are derived by the deformation of a large Mesozoic carbonate shelf, which connected the Africa margin with Adria. It corresponds partly to the Hyblean-Pelagian Block [*Nigro and Renda*, 1999] or to the Siculo-Tunisian platform [in the sense of *Di Stefano et al.*, 1996]. A large part of this paleogeographic unit extends in the Sicily Channel and in the Hyblean Plateau [*Antonelli et al.*, 1992] and is partly deformed as the external element of the SFTB or represents its foreland.
2. The eastern sector that can be further subdivided in a northern zone (Palermo Mountains) and a central-southern zone (Sicani Mountains). In the northern zone the structural grain consists of imbricated platform and deepwater-derived thrust sheets, while the central-southern zone appears as a complex multilayer (Monti Sicani thrust system) consisting of “pellicular” thrusts made of deepwater carbonates and cherts that were deposited, since the Permian, in a slope to deepwater basin. The preferential décollement horizons in the original multilayer are located in the ductile Permian-Triassic layers, in the Cretaceous marly sediments and in the Serravallian-Tortonian clays. The amount of shortening across the eastern sector is considerably higher than the western one. According to *Lickorish et al.* [1999] the total shortening across southern Sicily increases from very small values of 5–10 km, in the west of Sciacca, to as much as 40 km in the east.

The Monti Sicani thrust system overthrusts, southward, the deformed zone of the Hyblean-Pelagian Block [*Grasso and Reuther*, 1988].

A wideband roughly oriented N-S from the San Vito Lo Capo to the Sciacca area (SVCS) shows a complex thrust imbrication and an oblique convergence between tectonic units pertaining to the two sectors. This is put in relation to the presence of a fault-controlled margin of the Hyblean-Pelagian Block by *Nigro and Renda* [1999] but also to lateral displacements (in the northernmost and more deformed units) associated with wide (up to 140°) clockwise rotations [*Channell et al*., 1990; *Oldow et al*., 1990]. The amount of rotations decrease progressively southward down to 50° and 20° in the lower Pleistocene sediments of the outermost thrust sheets [*Speranza et al*., 2000].

Both areas are affected by Neogene compressional deformations that are represented by reverse faults and reverse reactivations of early normal faults [*Giunta et al*., 2002] along previous weakness zones of the Hyblean-Pelagian Block boundary [*Casero and Roure*, 1994]. Along the SVCS, neotectonic strike-slip structures are mainly developed, such as reverse and strike-slip faults and macroscopic folds. Strike-slip tectonics is also supported offshore southern Sicily by transpressional or transtensional structures [*Reuther et al*., 1993]. Within the thrust stack, the interference pattern of the compressional structures reveals a complicated timing of deformation, where different shortening events took place in a complex system due to a thin-skinned deformation style.

2.1. Seismicity of the Belice Valley

Historical [*Guidoboni et al*., 2007] and recent earthquakes indicate that western Sicily is an active deformation zone. A major earthquake (Belice earthquake) occurred in 1968 along the SVCS. The earthquake sequence occurred in an area covered by Pliocene-Pleistocene mostly clayey sediments and alluvial deposits. Although in this area some superficial faults and fractures are evident, their role is highly uncertain, particularly for the incompatibility between their sizes and the magnitude of the main shock of the sequence ($M_w = 5.6$, according to *Morelli and Pondrelli* [1998]).

Several authors [*De Panfilis and Marcelli*, 1968; *Marcelli and Pannocchia*, 1971; *Bottari*, 1973] have relocated major events of the sequence, coming to conclusions generally very different either as regards the hypocentral depth or the geometric features of the area involved by the epicenters. Although these works lack an adequate uncertainty analysis, the variability of the results demonstrates the inadequacy of the constraint given by the experimental data.

It is not easy to recover the full set of recordings of the events of that sequence. Moreover, the seismic station closest to the epicentral area, when it was in operation, was that of the Seismological Observatory of Messina at a distance greater than 250 km. The second one was at least twice that distance away.

Anderson and Jackson [1987] studied the 15, 16, and 25 January 1968 events and estimated a magnitude $M_b = 5.4$ for the main shock. Their epicentral relocations suggest a N-S alignment, which cannot be related to any recent fault or major structural trend. They find a relatively shallow location for most of the events (between 1 km and 36 km). Because of the limited number of good quality experimental data and of the uncertainties about the location of the hypocenters, their calculated focal mechanisms (Figure 5) remain ambiguous because they are compatible either with a pure E-W thrust plane or with a prevalently right-lateral movement on a NNW striking, WSW dipping plane.

Because of the alignment of the relocated epicenters in a northerly direction, the authors suggest a NNW striking plane with strike-slip component as preferred rupture plane.

Monaco et al. [1996] contend that the available instrumental data show events distributed along a roughly north dipping plane and that the published fault plane solutions indicate pure thrusting on north dipping, ENE trending planes, or oblique slip with right-lateral component of motion along WSW dipping planes. This dynamics results in an approximate N-S shortening. Based on macroseismic effects they identify an elongation of the isoseismal ENE that is shown also by the epicentral distribution of events with $M > 4$. The authors point out that this area is located 20 km NW of the Sciacca-Rocca Ficuzza thrust fault, a possibly active regional morphotectonic feature (tentatively dated at 1.0–0.7 Myr). Their conclusion is that multiple ruptures might have occurred on a blind crustal thrust ramp located beneath the epicentral area.

Morelli and Pondrelli [1998] calculated a centroid moment tensor solution of the main shock, indicating an EW trending, N dipping, oblique thrust.

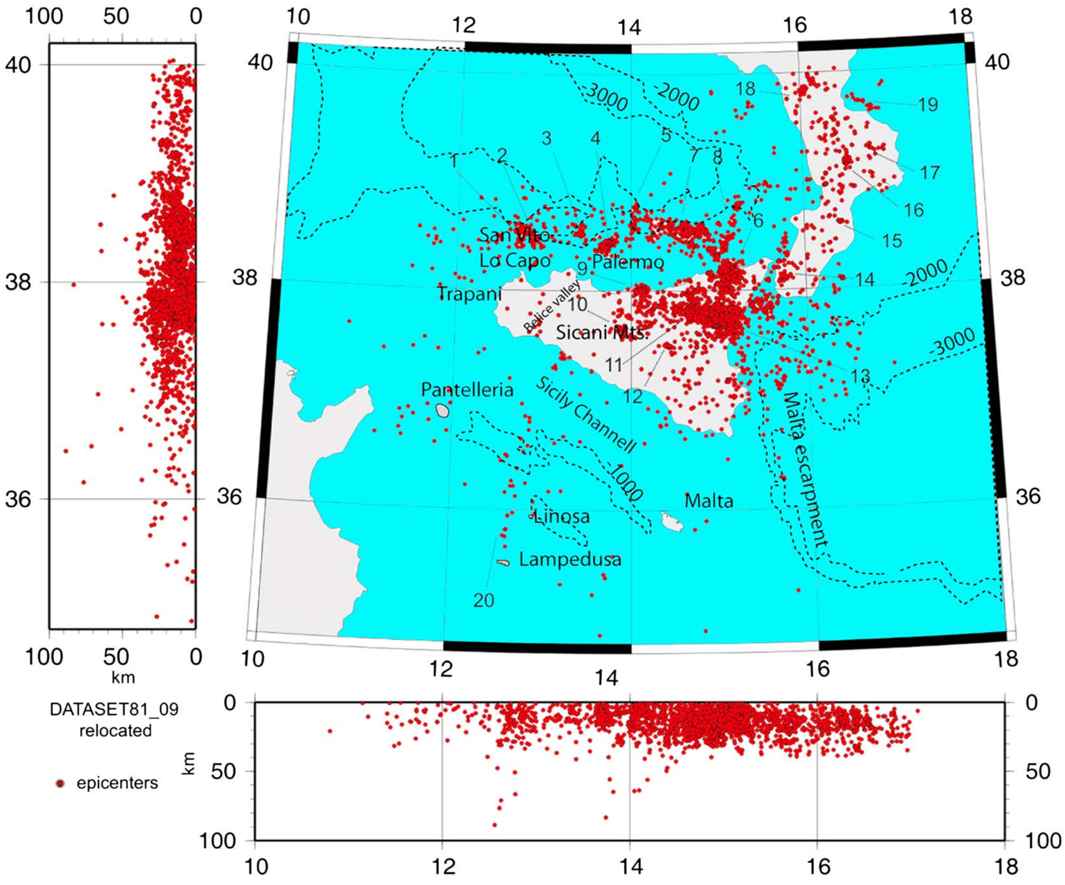

Figure 3. Pattern of the Sicilian seismicity and surrounding basins relocated using three-dimensional V_p and V_s models. Numbers are referred to the major seismic clusters [from *Calò et al.*, 2013].

Michetti et al. [1995] presented a paleoseismological study conducted in the epicentral area of the Belice sequence. On the basis of the effects produced by the earthquake sequence at the surface, they located two sites for trenching at Molino Nuovo and Monte Porcello, where the authors identified a previously unknown Quaternary fault (the Monte Porcello Fault, MPF). At this site, they excavate four trenches and found evidence of paleoseismicity. They concluded that the MPF is capable of producing coseismic surface displacement larger than those observed in 1968 and probably was broken during the 1968 earthquake. The geometry and kinematics of the MPF are consistent with a regional, NNW-SSE trending, right-lateral strike-slip zone within the Belice region.

3. Geophysical Studies Based on Local Earthquake Tomography

The seismicity of western Sicily and Sicily Channel is mostly characterized by crustal (10–20 km) focal depth and moderate magnitudes [*Galea*, 2007; *Chiarabba et al.*, 2005]. In the past, seismicity studies of this region have suffered from poor hypocentral location accuracy, especially in the case of earthquakes occurring in Sicily Channel. This is due to the inadequacy of the network coverage, especially before 1980, to locate small-size events that occurred in this area. However, since 1980 the number of stations operated by Istituto Nazionale di Geofisica e Vulcanologia (INGV) in the whole national territory has dramatically increased, making available a large amount of seismic recordings also for low-magnitude events, even in the Pelagian Archipelago. The improvement of the network together with the development of more sophisticated techniques of tomography and earthquake location allowed the main pattern of the seismicity to be described and several clusters of hypocenters to be associated with the main active structures of this region.

Recent studies [*Calò and Parisi*, 2014] showed that the hypocenters in the study area are highly clustered, suggesting that active structures accommodate the stress due to the active tectonics of the region (Figure 3). A relatively high hypocentral density exists between the Pantelleria depression and the Malta and Lampedusa

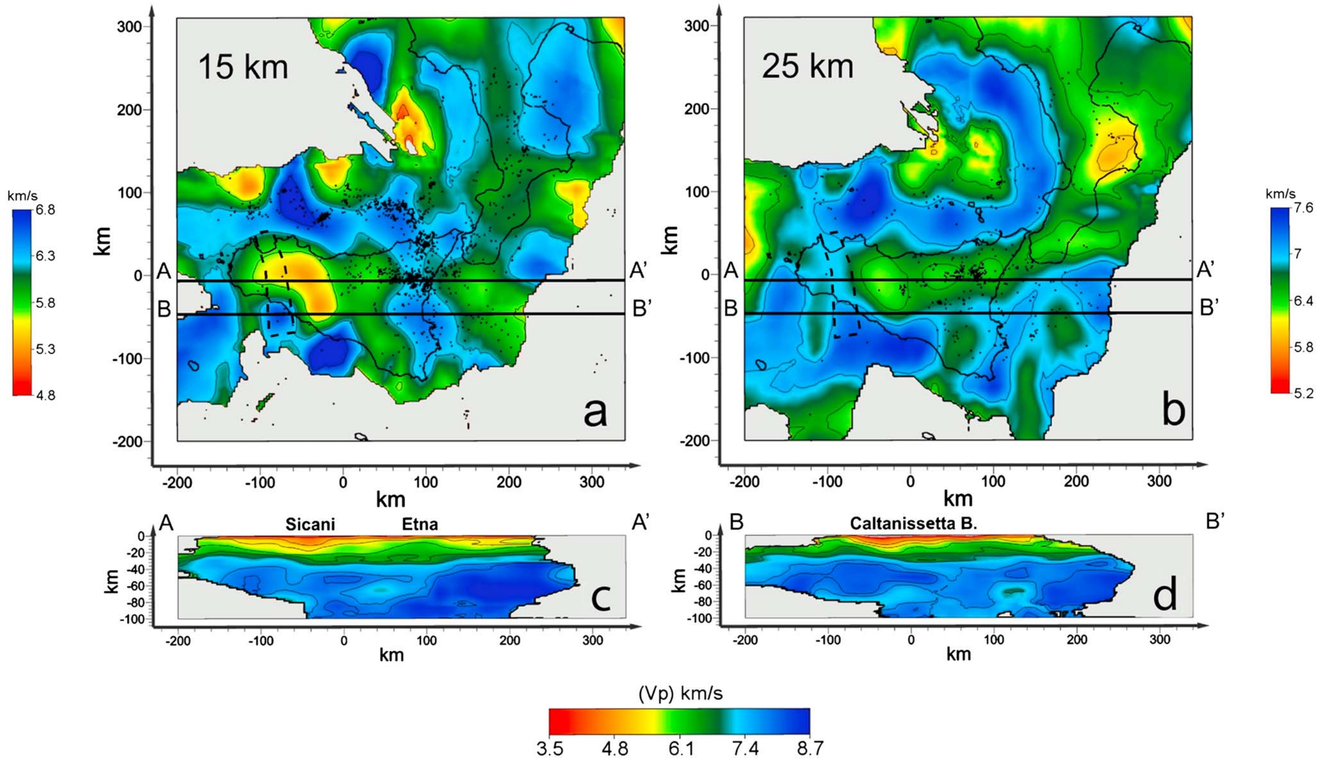

Figure 4. *P* wave seismic velocity model of the Sicilian area at 15 and 25 km depths. The black dots are the projections of the seismic events used to calculate the velocity model and located within ±2.5 km from the slice [from *Calò et al*., 2013]. The bold black lines are the projections of the two vertical sections A-A′ and B-B′ reported below. (a) The horizontal section of the V_p model at 15 km depth reports an extended low-velocity body beneath the central-western Sicily roughly oriented in E-W direction and bending southward in central Sicily. The westernmost edge of this body starts in the San Vito Lo Capo-Sciacca area (SVCS; dotted polygon). However, at this depth, the low V_p region involves most of the central-western part of the Sicily making difficult the observation of a clear pattern separating the region along the SVCS. (b) The slice at depth of 25 km clearly shows a low V_p area located beneath the Calabria and northern Sicily matching the position of the Apennine-Maghrebian chain and ending in the SVCS area.

ones (Figure 3, cluster number 20). Earthquakes in this area occur to depths down to 60–80 km and with local magnitudes reaching 4.7 in few cases. Moreover, *Calò and Parisi* [2014] proposed the existence of a unique large structure (some hundreds of kilometers long) running from the volcanic island of Linosa to Sicily. The focal mechanisms of the largest events ($M > 4$) and the relocated seismicity associated with this large structure are compatible with a system mainly dominated by a right-lateral strike slip of subvertical faults roughly oriented N-S [*Calò and Parisi*, 2014].

Seismic tomography of the area [*Calò et al*., 2013] imaged the main geological structures of the crust and upper mantle of Sicily and surrounding basins. To reconstruct three-dimensional models of the *P* and *S* seismic velocities body wave travel times (first arrivals of *P* and *S* waves) from local and regional seismicity were used. The applied technique combines a double-difference inversion method (tomoDD) [*Zhang and Thurber*, 2003] with a postprocessing procedure (weighted average model) [*Calò*, 2009; *Calò et al*., 2009, 2012] that improves both the resolution and the reliability of the models and provides parameters (e.g., the standard deviation of the velocity estimates) for assessing the incertitude on the velocity structures observed. The velocity models were obtained using 3445 events recorded by some 189 stations. The total amount of data consisted of 56,225 *P* and 23,858 *S* wave travel times, complemented by 119,866 *P* and 49,262 *S* differential times. Synthetic tests, performed to assess the resolving power of the data and the procedure used, showed the suitability to discriminate seismic structures of dimension $(20 \times 20 \times 2)\ \mathrm{km}^3$ in the inland areas and $(40 \times 40 \times 5)\ \mathrm{km}^3$ in the offshore ones [*Calò et al*., 2013]. The average horizontal and vertical event location errors, estimated for the whole Sicilian area, are 1.44 km and 3.1 km, respectively.

Figure 4a shows the horizontal section of the V_p model at 15 km depth where the SVCS region (dashed polygon), as identified by geological and structural data, has been overlapped. The model reports an extended low-velocity body beneath the central-western Sicily roughly oriented in E-W direction and bending southward in central Sicily. The westernmost edge of this body starts in the SVCS zone. However, at this depth, the low V_p region involves most of the central-western part of the Sicily making it difficult the observation of a clear pattern separating the region along the SVCS zone. The slice at depth of 25 km (Figure 4b) clearly shows a low V_p area located beneath the Calabria and northern Sicily matching the position of the Apennine-Maghrebian chain and ending in the SVCS area. Therefore, in the lower crust, the SCVS represents a transition zone where large-scale structures, as the basement of the Sicilian chain, are interrupted. Furthermore, weak V_p velocity values are observed in the Sicily Channel elongated in N-S direction, at NE of the Pantelleria Island suggesting the presence of a narrow structure propagating offshore as a possible prosecution of the SVCS transfer zone.

Figure 4c shows a W-E vertical section of the V_p model (A-A′ in Figures 4a and 4b) beneath Sicily. The black dashed polygon corresponds to the domain where the SCVS region has been observed in surface. This section shows how the Sicani units, which are marked by low-velocity values down to about 20 km depth, represent the easternmost border of the SCVS region. The lateral variation of the *P* wave seismic velocity at this depth is estimated of at least 0.5 km/s. At greater depth, we observe also a strong variation of the Moho depth, form 34–36 km below the Sicani to less than 30 km below the western sector. Figure 4d shows a V_p section (B-B′) crossing the Caltanissetta Basin and a part of the Sicily Channel. The features reported here are quite similar to the section A-A′ and show how the Caltanissetta Basin ends when the SCVS zone starts.

The information provided by the interpretation of the most recent seismic velocity models and of the relocated seismicity show that the SVCS transfer zone can be observed both onshore and offshore.

4. Structural Analysis Along the SVCS Band

The most important surface tectonic elements (thrust faults, strike-slip faults, and folds) recognized westward and eastward of SVCS allow a comparison between the deformation styles in the two different sectors. They are reported in a map of western Sicily (Figure 5) that was compiled on the base of original data and recent cartographic contributions [*Mauz and Renda*, 1996] (Carg project data available from ISPRA (Italian Institute for Environmental Protection and Research); http://www.isprambiente.gov.it/Media/carg/sicilia.html).

Detailed structural data collected in 10 sites (*a* to *l* in the map of Figure 5), and plotted in equal area lower hemisphere stereonets (Figure 5), show that the orientation of the minor structures (faults and folds) is consistent with the largest structures.

In the western sector the fold-and-thrust faults are oriented W-E and NE-SW, the last with a N or NW dip (sites a–c in Figure 5).

In the eastern sector the E-W oriented thrust fronts are connected to N-S or NW-SE trending lateral ramps facing the SVCS (e.g., Triona unit and Burgio unit). Here we can observe a progressive rotation of the fold axis direction (as measured in sites d–g in Figure 5) from roughly NE-SW to NW-SE, in agreement with *Nigro and Renda* [2002]. In particular, two fold systems are recorded in the northern part of this sector (Palermo and Galiello Mountains). The older system trends NNE-SSW to NE-SW, while the younger one trends approximately NW-SE (sites d and e in Figure 5). In the southern part of the eastern sector we observe two main fold systems trending approximately NW-SE and from NE-SW to ENE-WSW (sites f and g in Figure 5). In the four sites, the relationships between the two sets indicate that the NE-SW system is refolded by the NW-SE one.

Evidences of strike-slip motions along the SVCS are discontinuous. In the northern sector there is the well-known Castellammare Fault, a NW-SE trending high-angle fault that bounds eastward the San Vito Lo Capo Peninsula. Evidence of this fault is reported both offshore San Vito Lo Capo [*Agate et al.*, 2005] and onshore in the Castellammare arbor (Figure 5). A southern segment of this fault is observable along the western slope of Monte Bonifato. As postulated by *Mauz and Renda* [1996], this master fault (that matches in this sector the Segesta Fault of *Casero and Roure* [1994]) has controlled the opening of the Neogene Castellammare Basin.

Southward, in the Belice Valley, a small segment of a NNW-SSE strike-slip fault is observable at Monte Porcello as already reported in section 2 [*Michetti et al.*, 1995]. This high-angle fault, together with other adjacent faults, crosscuts upper Piacenzian to Gelasian calcarenites and clays and accommodates the differential shortening of the large-ramp anticline (Gibellina anticline) formed by Tortonian to lower Pliocene sediments.

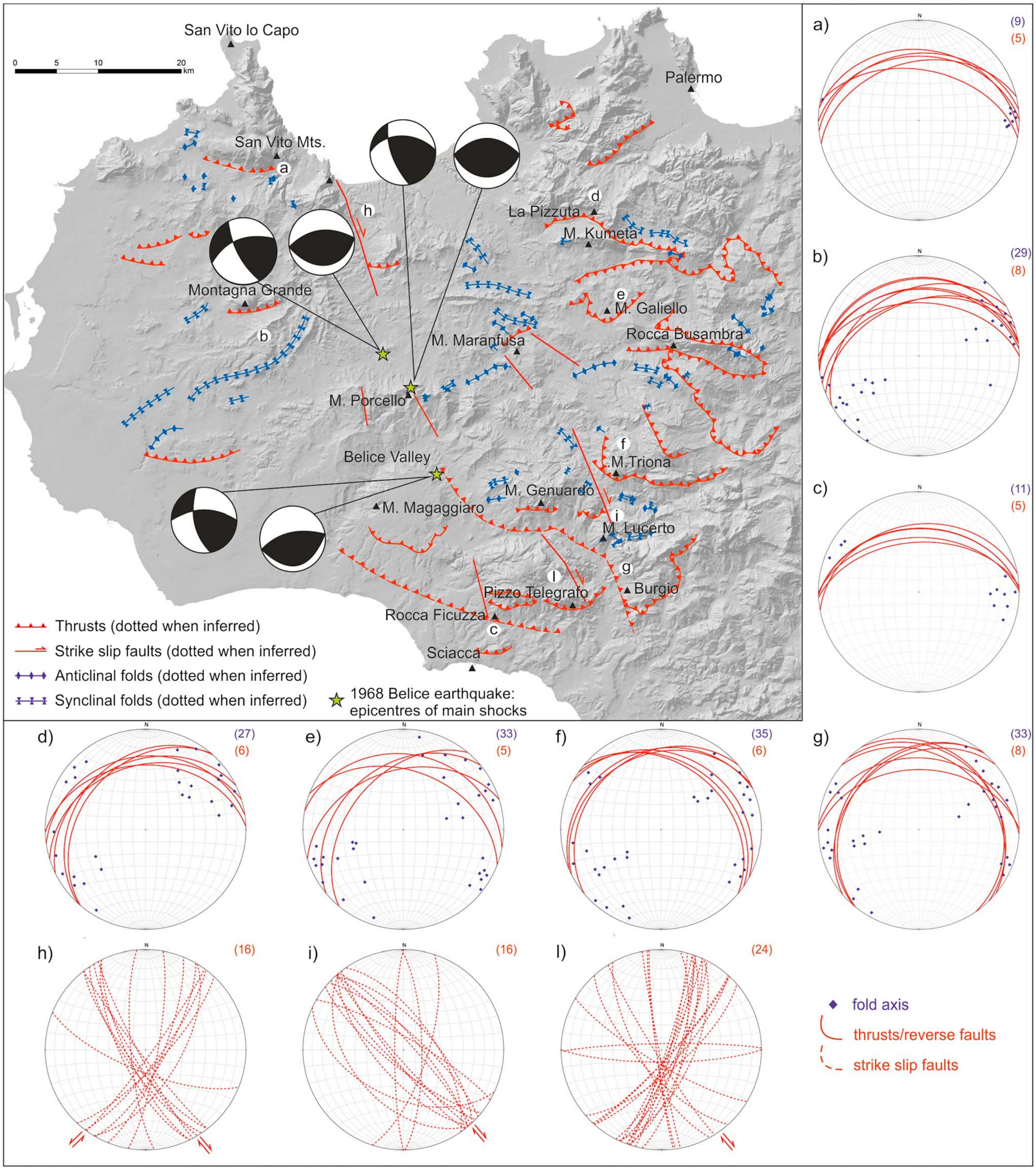

Figure 5. Schematic map of the western Sicily based on cartographic contributions [*Mauz and Renda*, 1996] (Carg project data available from ISPRA (Italian Institute for Environmental Protection and Research), http://www.isprambiente.gov.it/Media/carg/sicilia.htm, and Digital Terrain Model from www.sitr.regione.sicilia.it) showing the main fold axis, thrust, and strike-slip faults in western Sicily. The stereoplots (equal area, lower hemisphere) are relative to structural data collected in 10 sites (*a* to *l* in the map). They show how the orientation of the minor structures (faults and folds) is consistent with the largest structures. The green stars mark the epicentral distribution of the three main shocks of the 1968 earthquake sequence in western Sicily. Focal mechanism solutions show either right-lateral strike slip or thrust focal mechanisms [from *Anderson and Jackson*, 1987].

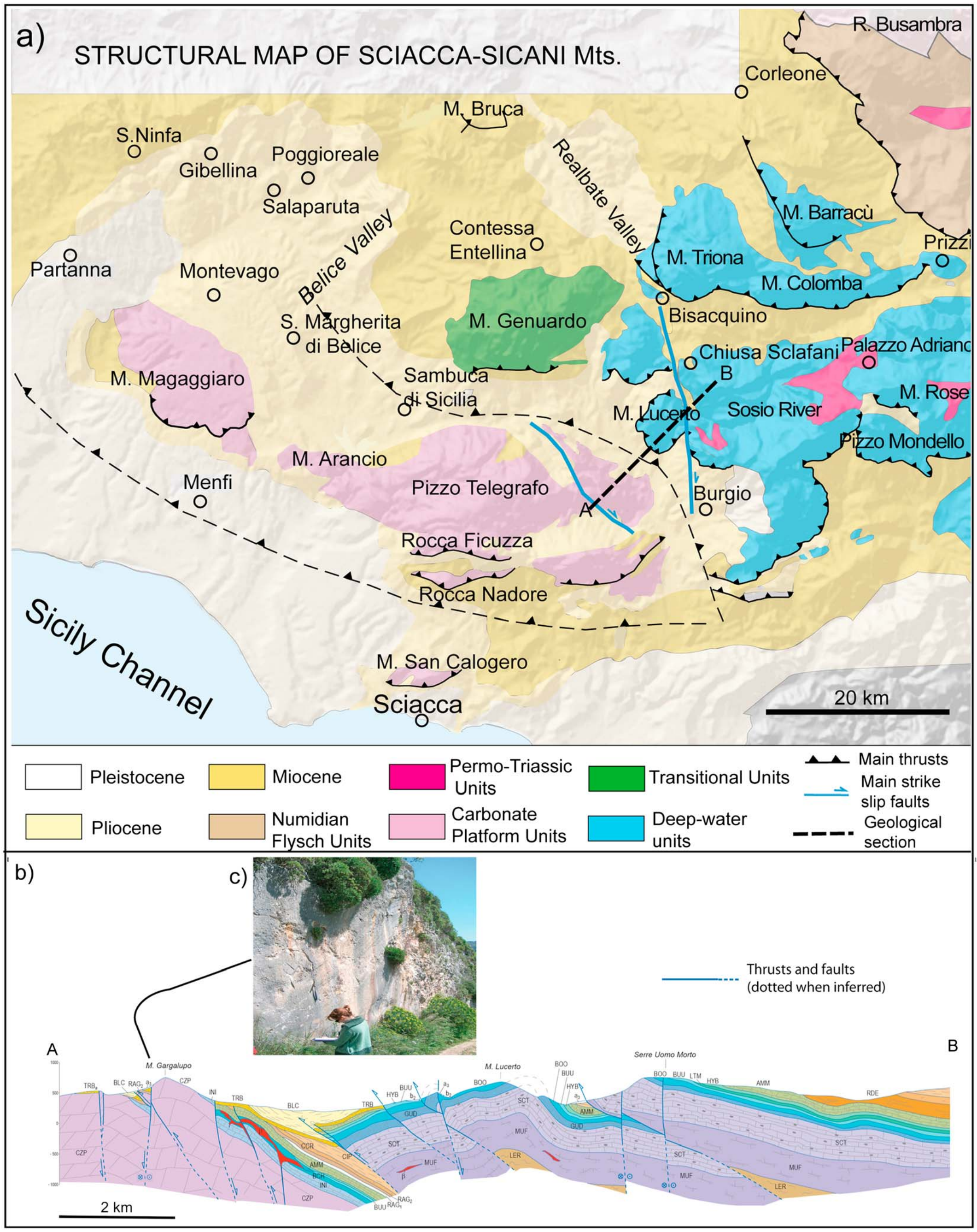

Figure 6. (a) Structural map of the Sciacca-Sicani Mountain area showing the NW-SE trending suture zone between the platform-derived thrust sheets and the deepwater ones. The Monte Genuardo unit (in green) has transitional characters (from Upper Triassic reefs to Jurassic slope and deepwater sediments). (b) A SW-NE oriented geological cross section across the suture zone, showing a lateral ramp leading a deepwater tectonic unit (Monte Lucerto) onto a platform unit (Monte Gargalupo is the easternmost termination of the Pizzo Telegrafo unit). CZP are Upper Triassic reefal carbonates, and SCT are time equivalent deepwater carbonates (*Halobia* cherty limestones) (modified after *Di Stefano et al.* [2013]).

In the southern zone of the SVCS good evidence of strike-slip motions with a NNW-SSE trend is in Realbate Valley (Figures 5 and 6) and at the easternmost termination of the Pizzo Telegrafo unit.

The Realbate Fault can be traced for about 10 km from the Realbate river valley to the Burgio village (Figures 5 and 6). This fault has most probably controlled the opening and the fills of two Pliocene-Pleistocene basins, namely, the Realbate and Burgio Basins.

At Pizzo Telegrafo NW-SE strike-slip faults are well exposed along the eastern sector, close to the Burgio Valley, where the contact between the deepwater Sicanian thrust sheets and the carbonate platform ones runs (see cross section in Figure 6b).

In this area the NW-SE fault set shows transpressional and right-lateral component of displacement as suggested by the kinematic indicators. Moreover, a Pleistocene transpressional regime in the external zones of the SFTB is documented by the interference pattern of Messinian-lower Pliocene folds refolded in late Pliocene early Pleistocene by N-S folds as observed in the Gela Nappe [*Ghisetti et al*., 2009].

5. Facies Analysis of the Mesozoic Carbonates

The distribution of the Upper Triassic facies in tectonic units of the SFTB is an important tool to reconstruct the paleogeography of the extensive carbonate platforms and deepwater basins that have floored the margins of the Ionian Tethys during Late Paleozoic and Mesozoic times. The facies analysis of the Upper Triassic carbonate platforms has been the object of several contributions in the past decades [*Abate et al*., 1977, 1982; *Catalano and D'Argenio*, 1982; *Senowbari-Daryan et al*., 1982].

The individuation of the Upper Triassic reefal rims at the edge of the carbonate shelves is of particular interest to evaluate the extension of the carbonate platforms and their relationships with the deepwater basins [*Di Stefano and Gullo*, 1997]. Moreover, the distribution of the reef-derived carbonate aprons that commonly were formed along slope or base-of-slope zones resulted in another important element to evaluate the extension of the carbonate platforms. The presence, in these aprons, among other reef-derived skeletal grains, of reworked reefal dweller benthic foraminifera provides an easy tool to prove the existence (at that time) of an adjacent Upper Triassic reef [*Di Stefano et al*., 1996].

Many authors pointed out how the marginal complexes of the Upper Triassic carbonate platforms can be differentiated in two end terms [*Flügel and Senowbari-Daryan*, 2001; *Flügel*, 2002; *Iannace and Zamparelli*, 2002]:

1. Microbial serpulid reefs typical at the margins of intraplatform basins of limited extension, with restricted circulation [*Berra and Jadoul*, 1996; *Braga and Lopez-Lopez*, 1989; *Zamparelli et al*., 1999];
2. Sponge-coral reefs (also known as Dachstein-type reefs), typical of high-energy, open marine environments. Coralline sponges and (subordinate) corals in association with a high-diverse community of reefal dwellers dominated these reefs [*Flügel*, 2002, and references therein; *Martindale et al*., 2013].

In Sicily, the first type of reef occurs only at the margins of the Streppenosa Basin, an intraplatform basin documented by boreholes in the subsurface of the Hyblean foreland (Mila member of the Noto Formation [*Frixa et al*., 2000]). The second type of reef is present from different thrust sheets cropping out in northern Sicily (Madonie and Palermo Mountains) and in southwestern Sicily (Sciacca and Monti Sicani areas).

Taking into account the above considerations, we focused our attention along the southern part of the SVCS (i.e., the Sciacca-Monti Sicani area), an area studied in detail to achieve the national geological map (sheet no. 619 "Santa Margherita di Belice" scale 1:50,000 [*Di Stefano et al*., 2013]). This sector offers a peculiar N-S transect across the outer and frontal zones of the chain where there are progressively attenuated effects of shortening and rotation of the different thrust sheets. In particular, on the base of the paleomagnetic data reported by *Speranza et al.* [2000] we consider the Pizzo Telegrafo structural unit as not rotated with respect to the stable Africa.

Detailed reconstructions of the distribution of the Upper Triassic facies in the different thrust sheets cropping out in this area of the SVCS (e.g., Pizzo Telegrafo unit and Monte Genuardo unit; Figure 6), coupled with the structural analysis, reveal the presence of Dachstein-type reefal limestones. They represent the edge of the large carbonate platform that is well known by boreholes and seismic reflection profiles in the subsurface of the western Sicily [*Catalano et al*., 2000; *Finetti*, 2005]. Moreover, the deepwater-derived thrust sheets extending eastward of this contact contain Upper Triassic reef-derived carbonate aprons (e.g., Monte Triona, Giuliana, and Sosio-Lucerto units [*Di Stefano et al*., 1996, 2013; *Cacciatore et al*., 2006]).

The presence along a west-east transect of all the facies types typical of an Upper Triassic carbonate platform-basin transition (i.e., from peritidal megalodont limestones to deepwater *Halobia* limestones through a sponge reef and slope apron) clearly indicates that the different thrust sheets belonged to a carbonate platform paleomargin and to the adjacent deepwater basin [*Di Stefano et al*., 2008; *Cacciatore*, 2010].

With regard to the deepwater basin (i.e., the Sicanian Basin), the stratigraphic data from Sicanian-derived thrust allowed us to document the existence of an original substrate that consisted of Permian-Carnian deepwater sediments [*Mascle*, 1979; *Catalano et al*., 1991; *Di Stefano et al*., 2014]. Focusing on the SVCS, we found thin tectonic imbricates made of Permian to Middle Triassic deepwater sediments wedged along the suture between platform and basin-derived thrusts (e.g., Portella Rossa, near Burgio [*Di Stefano et al*., 2013]; see geological section in Figure 6). According to *Di Stefano and Gullo* [1997], this substrate has been detached from the overlying Upper Triassic-Miocene succession during the Maghrebian orogeny and has originated strongly deformed tectonic complexes. Moreover, megabreccias deriving from Permian reefs in these deepwater sediments (e.g., Pietra di Salomone near Palazzo Adriano) document the presence of an adjacent platform rim [*Flügel et al*., 1991]. Thus, we believe that the sedimentary history of the carbonate platform-basin system, and of the paleotectonic discontinuity between them, is traceable since the Permian. As a whole, the first two steps schematically depicted in the cartoon of Figures 7a and 7b account for the above assumptions.

During Early Jurassic, the shallow water sedimentation continued on the Triassic platform (Inici Formation *Auct.*) even though local margin retreats suggest an extensional tectonic activity along the paleomargin (e.g., Monte Genuardo [*Di Stefano et al*., 1990]). Data collected by *Cacciatore and Di Stefano* [2008] and *Cacciatore* [2010] in this area document that the Dachstein-type reefs were overlapped by sandy margins with high-energy oolitic-skeletal grainstones, owing to the biotic crisis at the Triassic/Jurassic boundary, while radiolarian mudstones and wackestones were deposited in the adjacent deepwater basin (Figure 7c).

Along the paleotectonic alignment, multiple erosional or stepped discontinuity surfaces, swarms of Neptunian dikes associated with pillow-lava basalts, and thick megabreccia accumulations document a complex post-Sinemurian sedimentary dynamics of the platform-basin transition. In particular,

1. *Jurassic Neptunian dikes and submarine basalts* (Figure 7d). In the Pizzo Telegrafo unit, huge Neptunian dikes crosscut the Triassic/Lower Jurassic platform strata. They are filled up by grey to greenish ammonitic limestones of Middle to Upper Jurassic age [*Wendt*, 1969]. Moving eastward along the same unit, the intensity of the tectonic fragmentation increases, giving rise to in situ breccias [in the sense of *Castellarin*, 1982]. A well-exposed example is offered by the walls of an abandoned quarry facing the present-day platform/basin transition (Cava Russo Aiello, coordinates 37°38′40.79″N and 13°9′56.09″E [*Di Stefano et al*., 2013]).
   Very large submarine basalt flows (pillow lavas) are particularly concentrated across the SVCS. They lie between radiolarian limestones or radiolarites. Among others, we mention the classic localities of Monte Genuardo, Giuliana, and Burgio-Rifesi [*Trevisan*, 1935; *Mascle*, 1979]. Widespread basalts occur also in the Pizzo Telegrafo unit. On the base of trace elements *Lucido et al.* [1978] affirm that these basalts have a transitional to tholeitic affinity.
2. *Cretaceous-Eocene megabreccias* (Figure 7e). Very thick intercalations of megabreccias made of Triassic/Jurassic neritic carbonate extraclasts, associated with Jurassic pelagites and basalts, are wedged along the SVCS in Scaglia-type calcilutites. They formed thick aprons (up to 100–120 m in Monte Genuardo and Giuliana units) at the base of reactivated submarine fault escarpments as a result of giant failures. Slump scars deep into the Mesozoic substrate, sutured by Scaglia, occur in the Pizzo Telegrafo unit [*Di Stefano et al*., 2013].

The last two steps in Figures 7f and 7g depict the Miocene oblique thrusting and the Pliocene-Pleistocene transpression along the SVCS (see sections 4 and 7).

6. Geochemical Analysis of the Mantle-Derived Helium Fluxes

Along the studied alignment there are several thermal springs that are part of a large geothermal system. The estimated mantle-derived helium fluxes in the geothermal reservoir are up to 2–3 orders of magnitude greater than those of a stable continental area [*Caracausi et al*., 2005]. Such high helium fluxes cannot be provided by a long-lasting diffusion, thereby implying a more efficient helium transport. These high mantle-helium fluxes imply that helium is advectively transferred into the thermal system through deep fault systems.

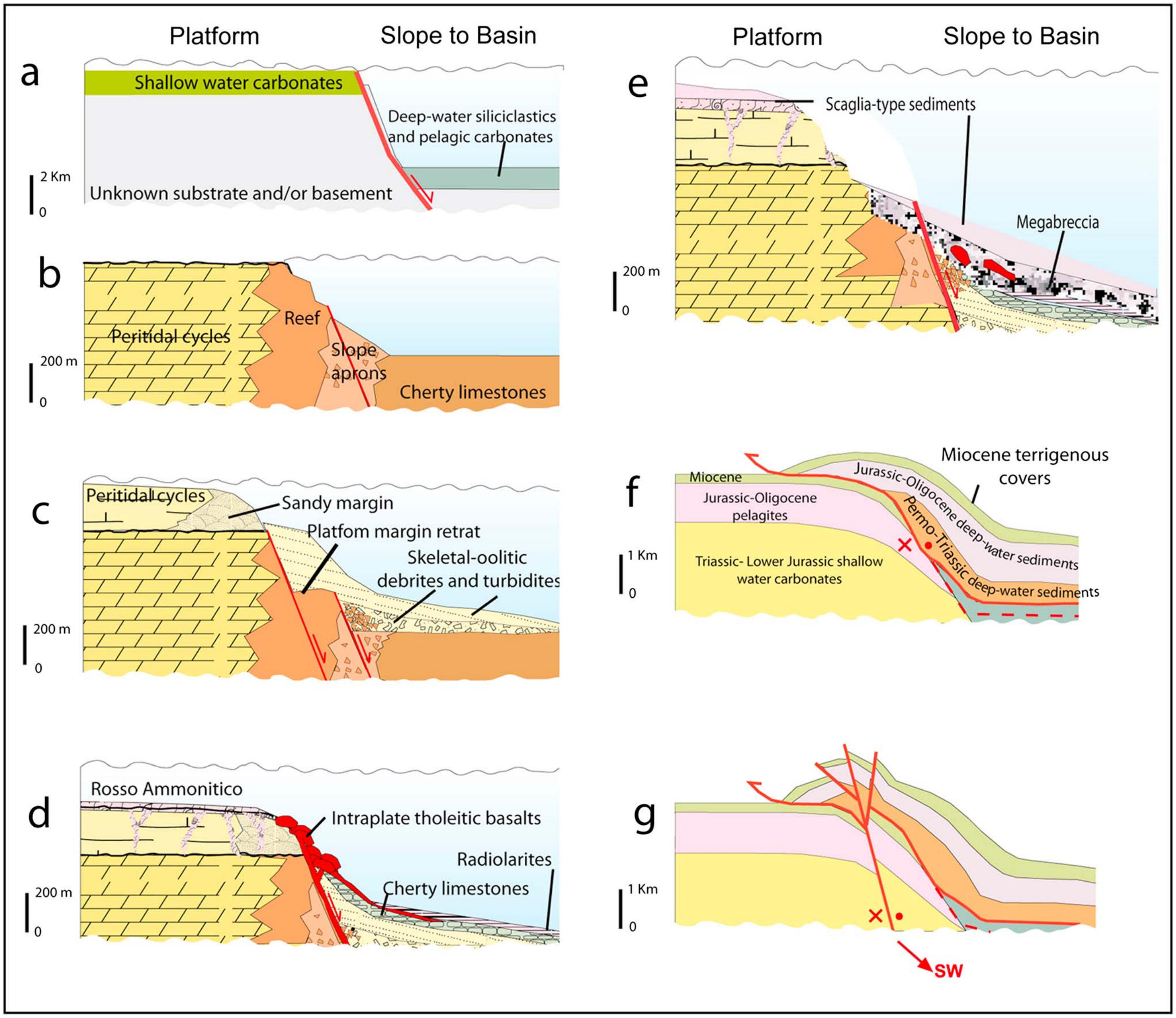

Figure 7. Cartoon (not to horizontal scale) depicting the tectono-sedimentary evolution of the carbonate platform-basin hinge zone in the Sciacca-Monti Sicani area of the SVCS (modified after *Di Stefano et al*. [2013]). (a) First step shows the presence of a platform-basin transition between the Hyblean-Pelagian Block and the Sicanian Basin (i.e., the westernmost termination of the Ionian Tethys) already in the Permian. (b) Schematic palinspastic section at the Late Triassic times showing the aggradation (up to 4 km) of the carbonate platform, edged by a Dachstein-type reef, and the sedimentation of slope aprons and *Halobia* cherty limestones into the basin. (c) Tectonic retreat of the platform margin close to the Triassic/Jurassic boundary and aggradation/progradation of the Lower Jurassic carbonate platform, edged by sandy margins. Debris flow and oolitic-skeletal calciturbidites in slope peribasinal areas. (d) Pliensbachian-Late Jurassic interval: platform drowning and condensed Rosso Ammonitico sedimentation; cherty limestone and bedded chert deposition into the basin; widespread submarine basaltic volcanism. (e) Cretaceous-Eocene interval: submarine fault escarpments, slope failures, stepped unconformities, and megabreccia wedge emplacement in Scaglia-type sediments. (f) Miocene: oblique convergence along the Mesozoic paleomargin due to the Maghrebian orogeny. Oblique thrusting and lateral ramp development between deep water and platform-derived thrust sheets. (g) Reactivation of the wrench deformations along the suture zone as right-lateral transpression during the Pliocene and Pleistocene.

The carbonate sequence of the western Sicily hosts three hydrothermal systems, from south to north Sciacca, Montevago, and Castellammare-Alcamo (Figure 8 and Table S1 in the supporting information). The temperature of the emerging waters ranges from 24°C to 60°C in the Sciacca Basin and from 28°C to 41°C and from 44°C to 50°C in Montevago and Castellammare-Alcamo Basins, respectively.

Previous investigations [*Caracausi et al*., 2005] highlighted that these systems fall in correspondence of regional tectonic discontinuities. In particular, Montevago Basin is located along the system of faults related to the 1968 Belice Valley earthquake ($M_w = 5.6$), and the chemistry of the waters showed earthquake-related modifications [*Favara et al*., 2001].

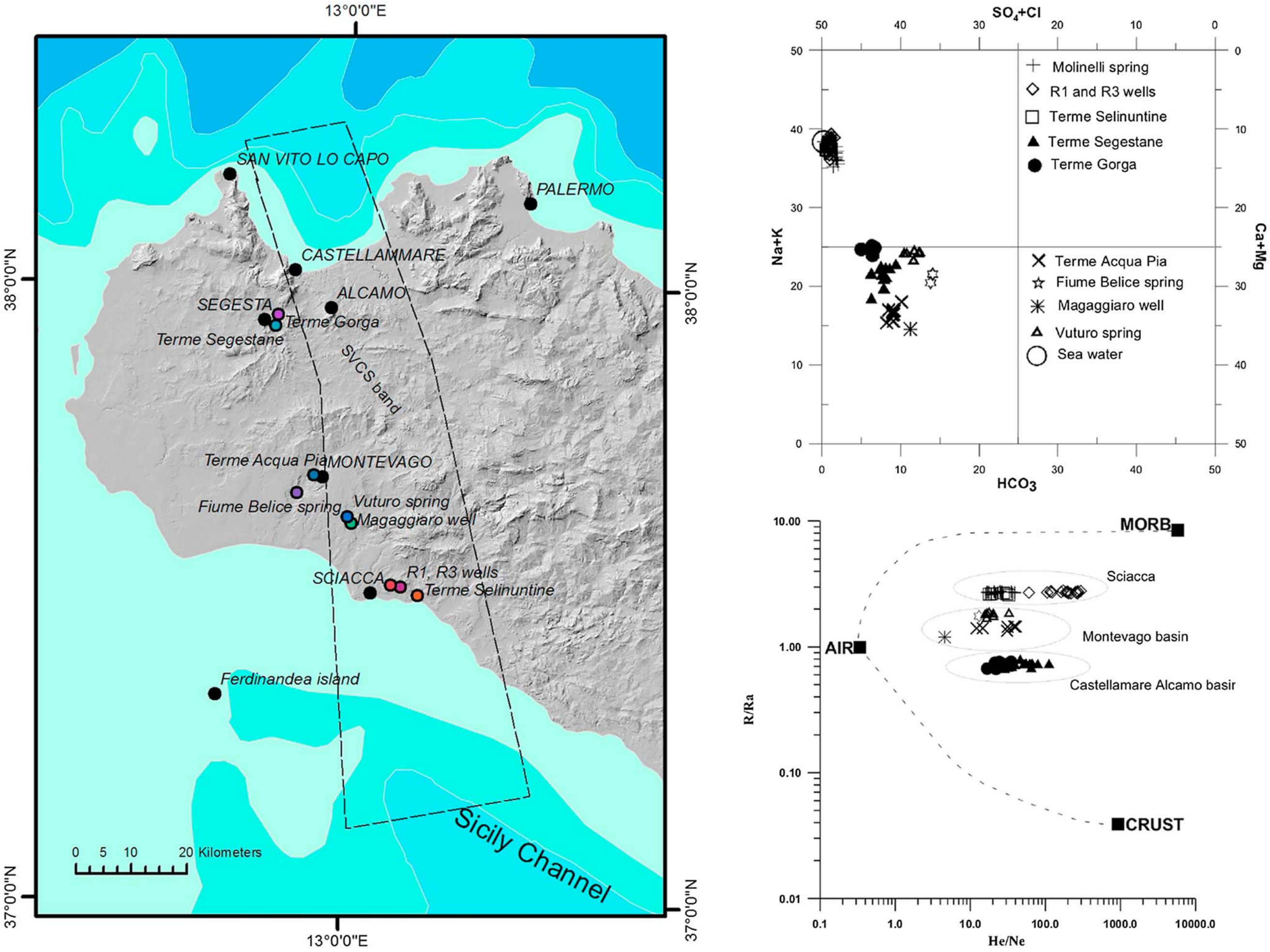

Figure 8. Location of the main thermal springs along the SVCS band and geochemical classification of the waters.

According to previous studies [*Alaimo et al.*, 1978; *Favara et al.*, 1998], two different families of thermal groundwater can be identified in western Sicily (Figure 8 and Table S1): chlorine-sulphate alkaline-Earth waters (Alcamo and Montevago Basins) and chlorine-sulphate alkaline waters (Sciacca Basin).

Favara et al. [2001] identified two different hydrogeochemical circuits for the above-mentioned hydrothermal systems. The first one may explain the Alcamo and Montevago thermal systems, suggesting a deep carbonate reservoir recharged by both carbonatic and selenitic waters in a mixing percentage of 70% and 30%, respectively. The other one, proposed for the Sciacca thermal system, is hypothesized as a deep carbonate reservoir fed by a mixture of seawater and waters equilibrated with carbonate rocks in the same percentage.

Dissolved gases in the waters of the three basins are CO_2 and N_2 rich with a relevant concentration of dissolved He, up to 2–3 orders of magnitude higher than the air-saturated water [*Capasso and Inguaggiato*, 1998]. Carbon isotopic signature of total dissolved carbon in the groundwaters highlights contribution of a deeply derived CO_2 in the thermal basin of western Sicily [*Grassa et al.*, 2006]. This CO_2 can derive from a mantle source and/or carbon dioxide produced from thermometamorphic decomposition of carbonate rocks.

The helium isotopic signature ranges from 0.7 Ra to 2.9 Ra (Ra is the $^3He/^4He$ in atmosphere, 1.39×10^{-6} [*Ozima and Podosek*, 2002]), and it increases from south (Sciacca) toward north (Castellamare-Alcamo). Helium is an inert gas, and because of the large difference between the isotope ratios of He coming from its possible sources (mantle, crust, and atmosphere) it represents a powerful tool to discriminate the contribution of different sources. Helium produced in the crust by radiogenic decay of U and Th is characterized by isotope ratio of 0.02 Ra; in contrast, the isotope ratio of mid-ocean ridge basalt-type helium is 8 ± 1 Ra [*Ozima and Podosek*, 2002].

The high $^{4}He/^{20}Ne$ ratio in the gases dissolved in the thermal waters of western Sicily demonstrates that air contamination of the sampled fluids was negligible. As a consequence it was possible to distinguish the three hydrothermal systems in terms of He mainly provided by only two sources: mantle and crust (Figure 8). Contributions of mantle-derived helium range from 50%, Sciacca system, to 10% in the Castellamare-Alcamo Basin. These contributions are significant especially in relation to the helium abundance in the investigated thermal systems higher than the content in air-saturated water.

The highest flux, found in the southernmost area near the Sicily Channel, where recent eruptions of the Ferdinandea Island occurred 32.18 km out to sea off Sciacca, has been associated with a clear excess of heat flow (up to 38 mW/m^2) [*Della Vedova et al*., 2001].

Both heat excess and mantle volatiles (He and CO_2) are almost certainly provided by mantle melts. The presence of mantle melts is more evident on the Sicily Channel side, probably linked to the recent volcanic activity of the Ferdinandea Island, which suggests a probable relationship with the rift of Pantelleria.

7. Discussion

The possibility that the different structural styles observed in western Sicily along the SVCS band depend by a differential thickness and composition of the sedimentary multilayer has been discussed for long time [*Vitale*, 1995; *Speranza et al*., 2000; *Monaco et al*., 2000; *Nigro and Renda*, 2002]. However, the stratigraphic evidences presented here document for the first time that the different tectonic units piled up in the SVCS derived from a Permian-Mesozoic platform-basin transition.

The presence of Dachstein-type reefs along the SVCS is of particular interest. Indeed, as reconstructed in the "classic" area of the Northern Calcareous Alps, the paleogeographic location of these reefs was along the Tethyan passive margin and typically arranged in shore-parallel barrier reefs [*Mandl*, 2000]. Along an orthogonal transect to this margin, the Triassic carbonate facies were separated (from onshore to offshore) into the following zones: (i) the Keuper belt (redbeds and evaporites), (ii) the Hauptdolomit and bedded Dachsteinkalk formations (supratidal to subtidal deposits), (iii) the Dachstein Formation or Dachsteinriffkalk (reefs facing deeper, open water), and (iv) the Hallstatt facies belt (periplatform pelagic sediments) [*Krystyn et al*., 2009]. A similar distribution is documented along a west-east transect from the Egadi Islands to the Monti Sicani, with the platform edge running along the SVCS. The paleogeographic reconstruction in Figure 9a (modified after *Zarcone and Di Stefano* [2010] and *Zarcone et al*. [2010]) is based on the Triassic facies distribution in Sicily coupled with the structural relationships among the different tectonic units of the STFB.

Several stratigraphic studies [*Di Stefano*, 1990; *Catalano et al*., 1991; *Flügel et al*., 1991; *Di Stefano and Gullo*, 1997] suggest that the Sicanian Basin, facing the Triassic platform edge, was a long-lasting deepwater area since the Permian. This corroborates the hypothesis that the reconstructed platform/basin transition may represent a heritage of the Permian-Mesozoic physiography of the western termination of the Ionian Tethys. In particular, it could be a deformed segment of the Ionian Tethys passive margin (Figure 9a), as we consider the Sicanian Basin as the westernmost termination (on thinned continental crust) of this oceanic branch of the Neotethys (see discussion in *Zarcone et al*. [2010]).

The sedimentary and volcanic records along the SVCS give evidence of an intense Jurassic-Eocene paleotectonic activity of this margin. A possible criticism to this assumption could be that all these sedimentary and volcanic features (mentioned in section 5) are widespread elements in the Mesozoic of Sicily as a consequence of the Jurassic extensional stress field [*Catalano and D'Argenio*, 1982]. However, we emphasize the intensity of these phenomena along the SVCS. In particular, the reactivation of the paleo-escarpment as consequence of the closure of the Alpine Tethys could have been the triggering factor for the emplacement of the huge megabreccia bodies in Cretaceous-Eocene Scaglia.

Even though with more or less irregular indentations, the outline of this margin was oblique or orthogonal to the main direction of contraction of the STFB. According to *Di Stefano et al*. [1996], the paleogeographic trend of this margin toward south was turned at right angle to W-E, and it is, at present, inflected beneath the thrust belt in central-eastern Sicily [*Bianchi et al*., 1987]. Some authors speculate that it would continue in the Malta escarpment [*Di Stefano et al*., 1996; *Adam et al*., 2000, and references therein], where the crustal transition between the Hyblean Block and the Ionian abyssal plain is well constrained [*Torelli et al*., 1998; *Adam et al*., 2000; *Catalano et al*., 2000; *Finetti*, 2005].

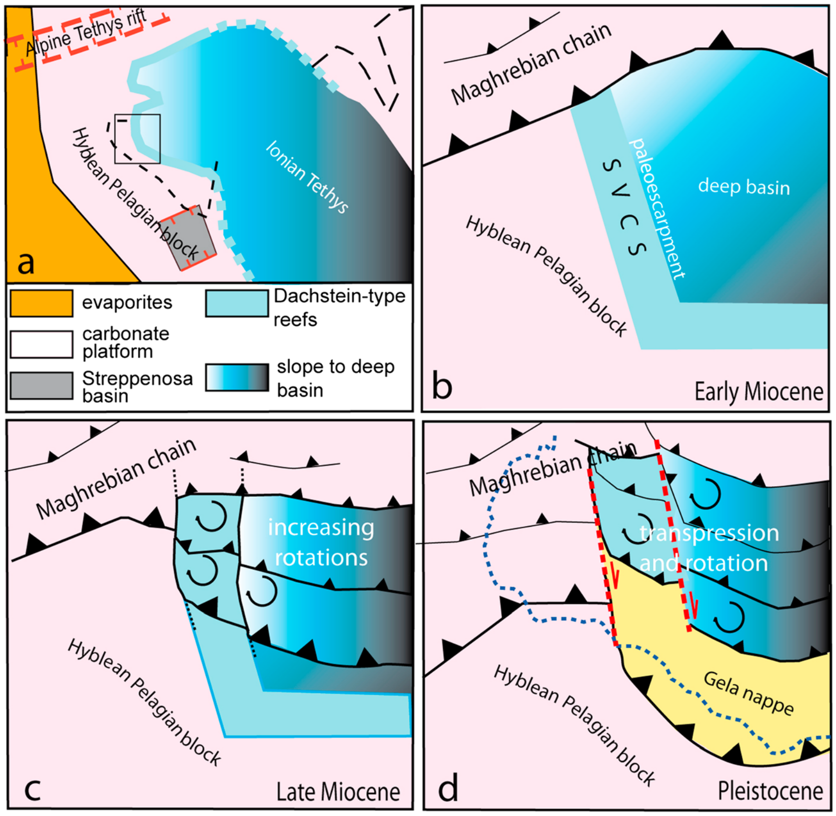

Figure 9. (a) Paleogeographic map of the western termination of the Ionian Tethys during Late Triassic times (modified after *Zarcone and Di Stefano* [2008]). (b–d) Miocene to Pleistocene kinematic evolution of the sector corresponding to the square area in Figure 9a. The nonparallel direction between the chain front and the SVCS discontinuity has resulted in oblique convergence, clockwise rotations, and right-lateral displacements. The colors adopted in Figures 9b–9d indicate the different Mesozoic sedimentary substrates involved in the collisional process (pink = carbonate platform; cyan = carbonate platform edge to slope; blue = deepwater carbonates and cherts).

Concerning the crustal characters along the SVCS, the seismic velocity models provided by the recent tomographies have allowed the interpretation of maps and vertical sections that clearly show the presence of a deep discontinuity. It extends at least in the whole crust (down to 30 km depth) separating the Sicanian units and their basement from the westernmost Sicily sector.

Furthermore, geochemical studies have shown the presence of rising gas and hot waters enriched in mantle elements. These data further support the presence of an active geodynamic crustal discontinuity representing the main triggering factor for the seismicity in this area.

In the SVCS geological survey, structural setting and kinematic analysis indicate that the different crustal and tectonostratigraphic setting of this area has favored differential shortening during the Neogene accretion of the Maghrebian chain, which resulted in a major rate in the eastern sector compared to the westernmost one in agreement with *Lickorish et al.* [1999].

Moreover, in the eastern sector of the SVCS two systems of fold-and-thrust faults (Palermo and Sicani Mountains) are present, unlike from the western one (San Vito and Sciacca Mountains), where only one fold-and-thrust fault system has been recorded. This indicates that the different deformation style existing between the two sectors is related to the progressive swinging and refolding of an older NE-SW fold system to NW-SE, as a consequence of the oblique convergence along the SVCS band. Paleomagnetic data collected by previous authors [*Channell et al.*, 1990; *Oldow et al.*, 1990; *Speranza et al.*, 2000] are in agreement with the observed clockwise rotations of the fold axis.

In particular, the effects of the oblique convergence are well observable in the southern sector of the SVCS (i.e., the outer zone of the chain) where the amount of shortening is reduced (Figure 6). In this area thin-skinned thrust sheets (i.e., Monti Sicani units) of Permian to Miocene deepwater sediments overthrust westward thicker structural units mostly formed of Upper Triassic-Lower Jurassic peritidal carbonates that pertain to the Hyblean-Pelagian Block, along a rough NNW-SSE alignment nearly parallel to the main south directed thrust propagation. The overthrust is accommodated by lateral ramps, as shown in Figures 5 and 6.

Experimental models [e.g., *Sokoutis et al.*, 2000; *Regard et al.*, 2005] corroborate the idea that the observed effects of differential shortening and rotations along a convergence zone are a result of a discontinuity separating areas with different rheological properties. In our case, the two sectors came into contact along the SVCS that roughly runs from the Castellammare Gulf to the area of Sciacca.

In extreme synthesis, the crustal and stratigraphic transition has favored the development of a regional lateral ramp, active since late Miocene, along which the deepwater-derived structural units were thrust over the carbonate platform units (Figures 9b–9d).

The correspondence of the crustal discontinuity and the oblique convergence zone is evident in the central-southern part of the SVCS band, while, in the northern sector (i.e., Palermo Mountains), the severe shortening and rotations induced in the inner zone of the chain have been able to obliterate the presence of this important discontinuity.

The model discussed here differs from previous interpretations on the structural evolution of western Sicily [e.g., *Giunta and Liguori*, 1973; *Catalano and D'Argenio*, 1982; *Avellone et al.*, 2010; *Albanese and Sulli*, 2012]. The most important differences concern the paleogeographic relationships between the deepwater basin and the carbonate platform that imply very different rates of shortening in the SFTB.

The oldest models [*Giunta and Liguori*, 1973; *Catalano and D'Argenio*, 1982, among others] assumed an alternation of carbonate platforms and intervening basins together with an orientation more or less parallel to the SFTB. More recently *Catalano and Di Maggio* [1996] and *Catalano et al.* [2000, 2013], on the base of surface data and seismic profiles, located the deepwater basins in a more internal position with respect to the carbonate platform.

Differently, our model implies a platform-basin transition from west to east, roughly orthogonal to oblique to the main direction of contraction. As highlighted by *Meghraoui and Pondrelli* [2012], when the plate boundary is oblique with respect to the convergent motion, an angular difference between the shortening directions and the convergence takes place. The authors interpreted this zone along the plate boundary as a restraining bend with significant transpressive deformation. In this light, we interpreted the imbrication of deepwater structural units over the carbonate platform ones, in the southernmost sector, as a result of the oblique thrusting along the SVCS. This imbrication only needs a moderate rate of shortening. This model suggests that some caution is needed on the interpretation of seismic lines running parallel to the SVCS zone. These profiles can in fact cross low-angle lateral ramps distorting the extent of shortening and consequently the palinspastic reconstructions.

On the whole, the integration of the data reported in this paper is in favor of the presence of an active geodynamic crustal discontinuity inherited from an ancestral (Permian) rifted margin. This discontinuity goes beyond the tectonic feature of a strike-slip fault as postulated by *Casero and Roure* [1994] and represents a first-order element for the seismicity in this area.

8. Conclusions

The integrated stratigraphic, structural, geophysical, and geochemical study of western Sicily points to a variation of the crustal characters along a band roughly north-south oriented from the Castellammare Gulf to the Sciacca area. The seismic tomography indicates that this band corresponds to an eastward transition from a normal continental crust to a thinned crust.

The stratigraphic architecture of western Sicily reflects the crustal differences highlighted by the seismic tomography as well as the subsidence history of the two sectors, which is remarkably different. Thick carbonate platform successions extend in the western sector (Hyblean-Pelagian structural units), while in the eastern zone deepwater sediments (Imerese-Sicanian structural units) have been accumulated in the Permian-Mesozoic and Tertiary. Moreover, the restored outline of the Mesozoic platform margins and slope aprons in the Sciacca and Monti Sicani areas matches the crustal transition and accounts for the presence of a paleotectonic shear zone that was reactivated several times either as transtensional or transpressional faults.

The different facies development in the area supports the idea that the different crustal characters reflect the Permian-Mesozoic physiography of the western termination of the Ionian Tethys (i.e., they represent a deformed segment of the Ionian Tethys margin).

The geological survey and the structural and kinematic analyses indicate that the different crustal and stratigraphic setting in this area has favored a differential shortening during the Neogene accretion of the Maghrebian chain, resulting in major rates in the eastern sector compared to the westernmost one. Along the discontinuity zone, oblique thrusting associated with clockwise rotations and wrench motions has accommodated the differential shortening.

The Gulf of Castellammare (in the north) and the westward limit of the arched front of the Gela Nappe (in the south) are the results of the differential deformations between these two sectors of the chain.

The epicenter distribution of earthquakes, the geochemical and geophysical anomalies, and the existence of recent faults, often with lateral component of motion, induce to consider the SVCS band as a zone of tectonic weakness. Along this band a potential geothermal resource but also a seismogenetic source that have to be deeply investigated is located.

Acknowledgments
Instrumental seismicity data used to perform the seismic tomography of *Calò et al.* [2013] are extracted from the "Bollettino Sismico," edited by the INGV (Istituto Nazionale di Geofisica e Vulcanologia), available at the website of the National Earthquake Centre (iside.rm.ingv.it). We thank D. Iacopini (University of Aberdeen), an anonymous reviewer, and the Editor for their fruitful comments that have largely improved the quality of the paper. We also thank A. Husker (UNAM, University of Mexico) for helping us on the improvement of the written form. Financial support was provided by Prin 2008, Carg Santa Margherita di Belice, and UNIPA PD_AUTF_005550 granted to P.D.

References

Abate, B., R. Catalano, B. D'Argenio, P. Di Stefano, and R. Riccobono (1977), Relationships of algae with depositional environments and faunal assemblages of the Panormide carbonate platform, Upper Triassic, northwestern Sicily, in *Fossil Algae*, edited by E. Flügel, pp. 293–313, Elsevier, Berlin.

Abate, B., R. Catalano, B. D'Argenio, E. Di Stefano, P. Di Stefano, G. Lo Cicero, L. Montanari, C. Pecoraro, and P. Renda (1982), Evoluzione delle zone di cerniera tra Piattaforme Carbonatiche e Bacini nel Mesozoico e nel Paleogene della Sicilia occidentale, in *Guida alla Geologia della Sicilia Occidentale. Guide Geologiche Regionali*, edited by R. Catalano and B. D'Argenio, pp. 53–81, Soc. Geol. It., Palermo, Italy.

Adam, J., C. D. Reuther, M. Grasso, and L. Torelli (2000), Active fault kinematics and crustal stresses along the Ionian margin of southeastern Sicily, *Tectonophysics*, *326*(3–4), 217–239.

Agate, M., M. Mancuso, and G. Lo Cicero (2005), Late Quaternary sedimentary evolution of the Castellamare Gulf (north-western Sicily offshore), *Boll. Soc. Geol. Ital.*, *124*, 21–40.

Alaimo, R., M. Carapezza, G. Dongarra, and S. Hauser (1978), Geochimica delle sorgenti termali siciliane, *Rend. Soc. Ital. Mineral. Petrol.*, *34*(2), 577–590.

Albanese, C., and A. Sulli (2012), Backthrusts and passive roof duplexes in fold-and-thrust belts, *Tectonophysics*, *514–517*, 180–198.

Anderson, H., and J. Jackson (1987), Active tectonics in the Adriatic region, *Geophys. J. R. Astron. Soc.*, *91*, 937–983.

Antonelli, M., R. Franciosi, G. Pezzi, A. Querci, G. P. Ronco, and F. Vezzani (1992), Paleogeographic evolution and structural setting of the northern side of the Sicily Channel, *Mem. Soc. Geol. Ital.*, *41*, 141–157.

Argnani, A. (1989), The Gela Nappe evidence of accretionary mélange in the Maghrebian foredeep of Sicily, *Mem. Soc. Geol. Ital.*, *38*, 419–428.

Avellone, G., M. R. Barchi, R. Catalano, M. Gasparo Morticelli, and A. Sulli (2010), Interference between shallow and deep-seated structures in the Sicilian fold-and-belt, Italy, *J. Geol. Soc. London*, *167*, 109–126.

Berra, F., and F. Jadoul (1996), Norian serpulid and microbial bioconstructions: Implications for the platform evolution in the Lombardy Basin, *Facies*, *35*, 143–162.

Bianchi, F., S. Carbone, M. Grasso, G. Invernizzi, F. Lentini, G. Longaretti, S. Merlini, and F. Mostardini (1987), Sicilia Orientale: Profilo geologico Nebrodi-Iblei, *Mem. Soc. Geol. Ital.*, *38*, 429–458.

Bottari, A. (1973), Attività sismica e neottettonica della Valle del Belice, *Ann. Geofis.*, *26*, 55–84.

Braga, J. C., and J. R. Lopez-Lopez (1989), Serpulid bioconstructions at the Triassic-Liassic boundary in Southern Spain, *Facies*, *21*, 1–10.

Cacciatore M. S. (2010), Architettura ed evoluzione delle facies sedimentarie di una zona di raccordo piattaforma carbonatica–bacino al passaggio Triassico-Giurassico: Area di Sciacca-Monti Sicani (Sicilia), PhD thesis, Dipartimento di Geol. e Geod. dell'Univ. di Palermo.

Cacciatore, M. S., and P. Di Stefano (2008), Triassic/Jurassic carbonates from western Sicily: Their facies and implications for the end-Triassic biotic crisis, *Rend. Online Soc. Geol. Ital.*, *2*, 57–60.

Cacciatore, M. S., P. Di Stefano, and R. Rettori (2006), Carbonate platform-basin systems in Sicily around the Triassic/Jurassic boundary: New data from the Campofiorito area (Sicani Mountains, western Sicily), in *Quaderni del Museo Geologico "G.G." Gemmellaro*, vol. 9, edited by P. Di Stefano and G. Buccheri, pp. 41–54, La Tipolitografica, Palermo, Italy.

Calò M. (2009), Tomography of subduction zones using regional earthquakes: Methodological developments and application to the Ionian slab, PhD thesis, EOST-Univ. de Strasbourg, pp. 1–134. [Available at http://tel.archives-ouvertes.fr/tel-00438598/en/.]

Calò, M., and L. Parisi (2014), Evidences of a lithospheric fault zone in the Sicily Channel continental rift (southern Italy) from instrumental seismicity data, *Geophys. J. Int.*, *199*(1), 219–225.

Calò, M., C. Dorbath, D. Luzio, S. Rotolo, and G. D'anna (2009), Local earthquake tomography in the Southern Tyrrhenian region of Italy: Geophysical and petrological inferences on the subducting lithosphere, in *Subduction Zone Geodynamics, Frontiers in Earth Sciences*, edited by S. Lallemand and F. Funiciello, pp. 85–99, Springer, Berlin.

Calò, M., C. Dorbath, D. Luzio, S. G. Rotolo, and G. D'Anna (2012), Seismic velocity structures of southern Italy from tomographic imaging of the Ionian slab and petrological inferences, *Geophys. J. Int.*, *191*(2), 751–764.

Calò, M., L. Parisi, and D. Luzio (2013), Lithospheric *P* and *S* wave velocity models of the Sicilian area using WAM tomography: Procedure and assessments, *Geophys. J. Int.*, *195*(1), 625–649.

Capasso, G., and S. Inguaggiato (1998), A simple method for the determination of dissolved gases in natural waters: An application to the thermal waters from Volcano Island, *Appl. Geochem.*, *13*, 631–642.

Caracausi, A., R. Favara, F. Italiano, P. M. Nuccio, A. Paonita, and A. Rizzo (2005), Active geodynamics of the central Mediterranean Sea: Tensional tectonic evidences in western Sicily from mantle-derived helium, *Geophys. Res. Lett.*, *32*, L04312, doi:10.1029/2004GL021608.

Casero, P., and F. Roure (1994), Neogene deformations at the Sicilian-North Africa plate boundary, in *Peri-Tethyan Platforms*, edited by F. Roure, pp. 27–45, Ed. Technip, Paris.

Castellarin, A. (1982), Tettonica sinsedimentaria ed associazioni di facies carbonatiche (con principali riferimenti al Giurassico Sudalpino), in *Guida alla Geologia del Sudalpino Centro-orientale. Guide Geologiche Regionali*, *Suppl. C delle Mem Soc. Geol. It*., vol. XXIV, edited by A. Castellarin and G. B. Vai, pp. 79–95, Soc. Geol. It, Rome.

Catalano, R., and B. D'Argenio (1982), Schema geologico della Sicilia, in *Guida alla Geologia della Sicilia Occidentale*, *Guide Geol. Reg.*, *Mem. Soc. Geol. Ital*., vol. 24, edited by R. Catalano and B. D'Argenio, pp. 9–41, STASS, Palermo, Italy.

Catalano, R., and C. Di Maggio (1996), Sovrapposizione tettonica delle Unità Imeresi sulle Panormidi nei Monti di Palermo (Sicilia), *Nat. Sicil.*, *4*(20), 147–166.

Catalano, R., P. Di Stefano, and H. Kozur (1991), Permian circumpacific deep-water faunas from the western Tethys (Sicily, Italy)—New evidences for the position of the Permian Tethys, in *Paleogeography and Paleocenography of Tethys*, *Palaeogeogr. Palaeoclimatol. Palaeoecol*., vol. 87, edited by J. E. T. Channel, E. L. Winterer, and L. F. Jansa, pp. 75–108, Elsevier, Amsterdam.

Catalano, R., A. Franchino, S. Merlini, and A. Sulli (2000), Central western Sicily structural setting interpreted from seismic reflection profiles, *Mem. Soc. Geol. Ital.*, *55*, 5–16.

Catalano, R., V. Valenti, C. Albanese, F. Accaino, A. Sulli, U. Tinivella, M. Gasparo Morticelli, C. Zanolla, and M. Giustiniani (2013), Sicily's fold-thrust belt and slab roll-back: The SI.RI.PRO. seismic crustal transect, *J. Geol. Soc.*, *170*(3), 451–464.

Channell, J. E. T., J. Oldow, R. Catalano, and B. D'Argenio (1990), Paleomagnetically determined rotations in the western Sicilian fold and thrust belt, *Tectonics*, *9*, 641–660, doi:10.1029/TC009i004p00641.

Chiarabba, C., L. Jovane, and R. Di Stefano (2005), A new look to the Italian seismicity: Seismotectonic inference, *Tectonophysics*, *395*, 251–268.

De Panfilis, M., and L. Marcelli (1968), Il periodo sismico della Sicilia orientale iniziato il 14/1/1968, *Ann. Geofis.*, *21*, 343–422.

Della Vedova, B., S. Bellani, G. Pellis, and P. Squarci (2001), Deep temperatures and surface heat flow distribution, in *Anatomy of an Orogen. The Apennines and Adjacent Mediterranean Basins*, edited by G. B. Vai and I. P. Martini, pp. 65–76, Kluwer Acad., Dordrecht, Netherlands.

Di Stefano, P. (1990), The Triassic of Sicily and the southern Apennines, *Boll. Soc. Geol. Ital.*, *109*, 21–37.

Di Stefano, P., and M. Gullo (1997), in *Timescales and Basin Dynamics: Sicily, the Adjacent Mediterranean and Other Natural Laboratories*, edited by R. Catalano, Eurobasin School, Palermo, Italy.

Di Stefano, P., M. Gullo, and B. Senowbari-Daryan (1990), The Upper Triassic reef of Monte Genuardo (southwestern Sicily), *Boll. Soc. Geol. Ital.*, *109*, 103–114.

Di Stefano, P., A. Alessi, and M. Gullo (1996), Mesozoic and Paleogene megabreccias in southern Sicily: New data on the Triassic paleomargin of the Siculo-Tunisian platform, *Facies*, *34*, 101–122.

Di Stefano, P., M. S. Cacciatore, and G. Zarcone (2008), A Triassic carbonate platform edge in the Sciacca zone: Implications for the accretion of the Maghrebian chain in southwestern Sicily, *Rend. Online Soc. Geol. Ital.*, *2*, 79–82. [Available at www.socgeol.it.]

Di Stefano, P., P. Renda, G. Zarcone, F. Nigro, and M. S. Cacciatore (2013), Foglio 619 "Santa Margherita di Belice" della Carta Geologica d'Italia. Scala 1:50.000, Note illustrative, 192 pp., ISPRA-Reg. Sicil., SystemCart, Roma.

Di Stefano, P., M. Rigo, A. Tripodo, S. Todaro, and G. Zarcone (2014), New biostratigraphic data from the Ladinian pelagic limestones of Pizzo di Sant'Otiero–Madonie Mountains, Sicily, *Riv. Ital. Paleontol. Stratigr.*, *120*, 61–70.

Favara, R., F. Grassa, S. Inguaggiato, and F. D'amore (1998), Geochemical and hydrogeological characterization of thermal springs in western Sicily, Italy, *J. Volcanol. Geotherm. Res.*, *84*, 125–141.

Favara, R., F. Grassa, S. Inguaggiato, and M. Valenza (2001), Hydrogeochemistry and stable isotopes of thermal springs: Earthquake-related chemical changes along Belice Fault (western Sicily), *Appl. Geochem.*, *16*, 1–17.

Finetti, I. R. (Ed.) (2005), *CROP Project, Deep Seismic Exploration of the Central Mediterranean and Italy*, *Atlas in Geosci*., 1st ed., 779 pp., Elsevier, Amsterdam.

Flügel, E. (2002), Triassic reefs patterns, in *Phanerozoic Reef Patterns*, *Spec. Publ. of SEPM 72*, pp. 391–463, Soc. for Sediment. Geol., Tulsa, Okla.

Flügel, E., and B. Senowbari-Daryan (2001), Triassic reefs of the Tethys, in *The History and Sedimentology of Ancient Reef Systems*, *Top. in Geobiol*., vol. 17, edited by G. D. Stanley Jr., pp. 217–249, Springer, Berlin.

Flügel, E., P. Di Stefano, and B. Senowbari-Daryan (1991), Microfacies and depositional structure of allochthonous carbonate base-of-slope deposits: The Late Permian Pietra di Salomone Megablock, Sosio Valley (western Sicily), *Facies*, *25*, 147–186.

Frixa, A., M. Bertamoni, D. Catrullo, E. Trincianti, and G. Miuccio (2000), Late Norian-Hettangian paleogeography in the area between wells Noto 1 and Polpo 1 (S-E Sicily), *Mem. Soc. Geol. Ital.*, *55*, 279–284.

Galea, P. (2007), Seismic history of the Maltese Islands and considerations on seismic risk, *Ann. Geophys.*, *50*, 6.

Gessner, K., L. Gallardo, V. Markwitz, U. Ring, and S. Thomson (2013), What caused the denudation of the Menderes Massif: Review of crustal evolution, lithosphere structure, and dynamic topography in southwest Turkey, *Gondwana Res.*, *24*, 243–274.

Ghisetti, F. C., A. R. Gorman, M. Grasso, and L. Vezzani (2009), Imprint of foreland structure on the deformation of a thrust sheet: The Plio-Pleistocene Gela Nappe (southern Sicily, Italy), *Tectonics*, *28*, TC4015, doi:10.1029/2008TC002385.

Giunta, G., and V. Liguori (1973), Evoluzione paleotettonica della Sicilia Nord-Occidentale, *Boll. Soc. Geol. Ital.*, *92*, 903–924.

Giunta, G., F. Nigro, and P. Renda (2002), Inverted structures in western Sicily, *Boll. Soc. Geol. Ital.*, *121*, 11–17.

Grassa, F., R. Favara, G. Capasso, and S. Inguaggiato (2006), Chemical and isotopic composition of waters and dissolved gases in some thermal springs of Sicily and adjacent volcanic islands, Italy, *Pure Appl. Geophys.*, *163*, 781–807.

Grasso, M., and C. D. Reuther (1988), The western margin of the Hyblean Plateau: A neotectonic transform system on the SE Sicilian foreland, *Ann. Tecton.*, *2*(2), 107–120.

Guidoboni E., Ferrari G., Mariotti D., Comastri A., Tarabusi G., Valensise G. (2007), CFTI4-Med 2007—Catalogue of strong earthquakes in Italy and Mediterranean area from the 8th century B.C. to 2000. [Available at http://storing.ingv.it/cfti4med/.]

Iannace, A., and V. Zamparelli (2002), Upper Triassic platform margin biofacies and the paleogeography of southern Apennines, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *179*, 1–18.

Krystyn, L., G. W. Mandl, and M. Schauer (2009), Growth and termination of the Upper Triassic platform margin of the Dachstein area (Northern Calcareous Alps, Austria), *Aust. J. Earth Sci.*, *102*, 23–33.

Lickorish, W. H., M. Grasso, R. W. H. Butler, A. Argnani, and R. Maniscalco (1999), Structural styles and regional tectonic setting of the "Gela Nappe" and frontal part of the Maghrebian thrust belt in Sicily, *Tectonics*, *18*, 669–685, doi:10.1029/1999TC900013.

Lucido, G., P. M. Nuccio, M. Valenza, and G. Giunta (1978), Magmatism in the Sicano Basin (Sicily) related to Meso-Cenozoic tectonics of the North-African paleomargin, *Min. Pet. Acta*, *22*, 55–69.

Mandl, G. W. (2000), The Alpine sector of the Tethyan shelf—Examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps, *Mitt. Österreichischen Geol. Ges.*, *92*, 61–78.

Marcelli, L., and G. Pannocchia (1971), Uno studio analitico sui dati ipicentrali di 10 terremoti avvenuti in Sicilia occidentale nel Gennaio 1968, *Ann. Geofis.*, *14*, 281–305.

Martindale, R. C., L. Krystyn, D. J. Bottjer, F. A. Corsetti, B. Senowbari-Daryan, and R. Martini (2013), Depth transect of an Upper Triassic (Rhaetian) reef from Gosau, Austria: Microfacies and community ecology, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *376*, 1–21.

Mascle, G. (1979), *Étude Géologique des Monts Sicani*, *Riv. It. Paleont. e Strat. Mem*., vol. 16, pp. 1–431, Dipartimento di Scienze della Terra, Milano.

Mauz, B., and P. Renda (1996), Tectonic features at the NW-coast of Sicily (Gulf of Castellammare), Implications for the Plio-Pleistocene structural evolution of the southern Tyrrhenian continental margin, *Stud. Geol. Camerti*, *1995/2*, 343–350.

Meghraoui, M., and S. Pondrelli (2012), Active faulting and transpression tectonics along the plate boundary in North Africa, *Ann. Geophys.*, *55*(5), 955–967, doi:10.4401/ag-4970.

Michetti, A. M., F. Brunamonte, and L. Serva (1995), Paleoseismological evidence in the epicentral area of the January 1968 earthquakes, Belice, southwestern Sicily, in *Perspectives in Paleoseismology*, *A.E.G. Spec. Publ*., vol. 6, edited by L. Serva and D. B. Slemmons, pp. 127–139, Peanut Butter Publ., Seattle, Wash.

Mitra, S. (1997), Evolution of salients in a fold-and-thrust belt: The effects of sedimentary basin geometry, strain distribution and critical taper, in *Evolution of Geological Structures in Micro- to Macro-scales*, edited by S. Sengupta, pp. 59–90, Chapman and Hall, London.

Monaco, C., S. Mazzoli, and L. Tortorici (1996), Active thrust tectonics in western Sicily (southern Italy): The 1968 Belice earthquake sequence, *Terra Nova*, *8*, 372–381.

Monaco, C., L. Tortorici, and S. Catalano (2000), Tectonic escape in the Sicanian Mountains (western Sicily), *Mem. Soc. Geol. Ital.*, *55*, 17–25.

Morelli, A., Pondrelli S. (1998) Il terremoto del Belice del 1968, paper presented at Conference “Trenta anni di terremoti in Italia: Dal Belice a Colfiorito,” Erice, Sicily, 14–18 July.

Nigro, F., and P. Renda (1999), Evoluzione geologica ed assetto strutturale della Sicilia centrosettentrionale, *Boll. Soc. Geol. Ital.*, *118*, 375–388.

Nigro, F., and P. Renda (2002), Forced mode dictated by foreland fault-indenter shape during oblique convergence: The western Sicily mainland, *Boll. Soc. Geol. Ital.*, *121*, 151–162.

Ogniben, L. (1969), Schema introduttivo alla geologia del confine Calabro-Lucano, *Mem. Soc. Geol. Ital.*, *8*, 453–763.

Oldow, J. S., J. E. T. Channel, R. Catalano, and B. D’Argenio (1990), Contemporaneous thrusting and large-scale rotations in the western Sicilian fold and thrust belt, *Tectonics*, *9*, 661–681, doi:10.1029/TC009i004p00661.

Ozima, M., and F. A. Podosek (2002), *Noble Gas Geochemistry*, 300 pp., Cambridge Univ. Press, London.

Regard, V., C. Faccenna, J. Martinod, and O. Bellier (2005), Slab pull and indentation tectonics: Insights from 3D laboratory experiments, *Phys. Earth Planet. Inter.*, *149*, 99–113.

Reuther, C. D., Z. Ben-Avraham, and M. Grasso (1993), Origin and role of major strike-slip transfer during plate collision in central Mediterranean, *Terra Nova*, *5*, 249–257.

Rosenbaum, G., G. Lister, and C. Duboz (2004), The Mesozoic and Cenozoic motion of Adria (central Mediterranean): A review of constraints and limitations, *Geodin. Acta*, *17*(2), 125–139.

Senowbari-Daryan, B., P. Schäfer, and B. Abate (1982), Obertriadische Rifle und rifforganismen in Sizilien, *Facies*, *6*, 165–184.

Sokoutis, D., M. Bonini, S. Medvedev, M. Boccaletti, C. J. Talbot, and H. Koyi (2000), Indentation of a continent with a built-in thickness change: Experiment and nature, *Tectonophysics*, *320*, 243–270.

Speranza, F., R. Maniscalco, M. Mattei, and R. Funiciello (2000), Timing and magnitude of rotations in the frontal thrust system of southwestern Sicily, *Mem. Soc. Geol. Ital.*, *55*, 95–102.

Tavarnelli, E., R. W. H. Butler, F. A. Decandia, F. Calamita, M. Grasso, W. Alvarez, and P. Renda (2004), Implications of fault reactivation and structural inheritance in the Cenozoic tectonic evolution of Italy, in *Special Volume of the Italian Geological Society for the IGC 32 Florence-2004*, pp. 209–222, Tipolitografia Di Virgilio, Chieti.

Torelli, L., M. Grasso, G. Mazzoldi, and D. Peis (1998), Plio-Quaternary tectonic evolution and structure of the Catania foredeep, the northern Hyblean Plateau and the Ionian shelf (SE Sicily), *Tectonophysics*, *298*, 209–221.

Trevisan, L. (1935), Studio geologico del centro eruttivo giurese di Giuliana in provincia di Palermo, *Period. Mineral.*, *6*(1), 1–65.

Vitale, F. P. (1995), Il segmento sicano della catena sud-tirrenica: Bacini neogenici e deformazione attiva, *Stud. Geol. Camerti Spec.*, 2, 491–507, Università di Camerino, Camerino, Italy.

Wendt, J. (1969), Die stratigraphisch-Paläogeographische Entwicklung des jura in Westsizilien, *Geol. Rundsch.*, *58*(3), 735–755.

Zamparelli, V., S. Cirilli, A. Iannace, and F. Jadoul (1999), Palaeotectonic and palaeoceanographic controls on microbial-serpulid communities in the Norian-Rhaetian carbonates of Italy: A synthesis, in *Bioevents and Integrate Stratigraphy of the Triassic and the Jurassic in Italy*, *Palaeopelagos Spec. Publ.*, vol. 3, edited by R. Colacicchi, G. Parisi, and V. Zamparelli, pp. 7–84, River Press, Rome.

Zarcone, G., and P. Di Stefano (2008), Mesozoic discontinuities in the Panormide carbonate platform: Constraints on the palaeogeography of the central Mediterranean, *Rend. Online Soc. Geol. Ital.*, *2*, 191–194.

Zarcone, G., and P. Di Stefano (2010), The Panormide carbonate platform (Sicily): An anomalous case in the evolution of Jurassic Tethyan Basins (La Piattaforma carbonatica panormide: Un caso anomalo nell’evoluzione dei bacini della Tetide Giurassica), *Ital. J. Geosci.*, *129*(2), 188–194.

Zarcone, G., F. M. Petti, A. Cillari, P. Di Stefano, D. Guzzetta, and U. Nicosia (2010), A possible bridge between Adria and Africa: New palaeobiogeographic and stratigraphic constraints on the Mesozoic palaeogeography of the central Mediterranean area, *Earth Sci. Rev.*, *103*, 154–162.

Zhang, H., and C. H. Thurber (2003), Double-difference tomography: The method and its application to the Hayward Fault, California, *Bull. Seismol. Soc. Am.*, *93*(5), 1875–1889.