BTA/TG/13-11

Title **Structural and lithological analysis of a foreland fold-and-thrust belt in the Umbria-Marche Apennines**

Students name **DIRK-JAN VAN VEEN**

Date **08/07/2013**

Title	:	Structural and lithological analysis of a foreland fold-and-thrust belt in the Umbria-Marche Apennines (Italy)
Author(s)	:	Dirk-Jan van Veen, in cooperation with Jitse Alsemgeest, Veerle Steenhuisen
Date	:	8 July 2013
Professor(s)	:	prof. dr. Giovanni Bertotti
Supervisor(s)	:	prof. dr. Giovanni Bertotti
TA Report number	:	**BTA/TG/13-11**

Postal Address : Section for Geoscience
Department of Geoscience & Engineering
Delft University of Technology
P.O. Box 5028
The Netherlands
Telephone : (31) 15 2781328 (secretary)
Telefax : (31) 15 2781189

Structural and lithological analysis of a foreland fold-and-thrust belt in the Umbria-Marche Apennines (Italy)

J. Alsemgeest [a], V. Steenhuisen [b], D.J. van Veen [b]

[a] *Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, De Boelelaan 1085-1087, 1081 HV Amsterdam, The Netherlands*
[b] *Department of Geoscience and Engineering, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands*

Received 5th of July 2013

Abstract

The geology in and around the Fiume Fiastrone valley (Umbria-Marche region, Italy) is controlled by a NW-SE striking fold and thrust belt of Neogene age. During a different stage SW-NE striking folds were created. The lithology in the area consists mainly of carbonates and carbonate shales of Mesozoic to Cenozoic age. The system has been analysed by means of morphological and structural analysis of exposed rock in the area around the Fiume Fiastrone valley. The geological situation before thrusting is proposed to be a SW-NE directed 8-10 km long anticline. Indications for this proposition are anticline-indicating orientations in the footwall at different locations with a maximum dip of 40 degrees. On the hanging wall the two nearly perpendicular folds created a 6 by 4 km dome structure that is bounded by the Sibillini thrust. This thrust accommodates 1800 m of lateral shortening; the Anidriti del Burano Fm. acts as its décollement. A literature study shows that NW-SE shortening started during the Quaternary; this would correspond to a shortening rate of roughly 0.1 mm/y in this direction. The implication of this theory is that the Sibillini thrust should show NW-SE compressional deformation. However, the outcrop of this thrust, at the hinge of the anticline, shows no considerable curvature over a length of about 1 km. Hence this observation does not confirm that theory. It may be possible though that the thrust fault exhibits curvature on a larger scale.

Keywords: fold-and-thrust belt; microfolds; foreland basin; Umbria-Marche Apennines

Introduction

The development of the Apennines thrust-and-fold belt has long been unclear, and as new ideas start to form the need for more detailed information becomes apparent. Although many studies have already been conducted on this subject, debate is still going on in matters concerning the order and magnitude of deformational events and the structural evolution.

The focus in this paper has been on these last two topics: based on previous papers on the development of the Apenninic fold-and-thrust belt and a field study of the Umbria-Marche area, the structural geology of the Monte Sibillini area has been analysed. This may give new constraints to the tectonic evolution of the area.

Fieldwork took place from the 27th of June to the 14th of May 2013 and has been completed by students of the Vrije Universiteit Amsterdam and the Technische Uniersiteit Delft. The location is the Sibillini Mountains, around Camporotondo del Fiastrone, Macerata, Italy, where the frontal anticline of the Appenines fold-and-thrust belt has been exposed.

The paper consists of three parts: the geological setting, the lithostratigraphy and the geologic features of the Sibillini area. The first two are mostly based on literature study, while the last is based on observations in the field. This paper includes six appendices, amongst which a stratigraphic column, multiple cross-sections, a geological map and several stereoplot diagrams.

1. Geological Setting

After assembly of the supercontinent Pangea and the Hercynian orogeny, dextral transtensional movements started to form between Laurasia and Gondwana during the early Permian (Gaetani, 2010). In the late Triassic, these transtensional movements developed into a rifting phase that would separate the two continents, creating the Central-Atlantic Ocean and the Alpine Tethys Sea by the late mid Jurassic (Stampfli, Borel, Marchant, & Mosar, 2002).It is in these processes that the Adriatic plate, a promontory of the African plate, was created.

Rifting propagated on the Gondwana continent opening the South-Atlantic Ocean. As a result of the new rifting direction, the African plate started moving in a counterclockwise direction towards Europe by the end of the Early Cretacious (Gaetani, 2010) (figure 1.1). During the Paleocene and Eocene, subduction of the Adriatic plate continued as the African plate continued its movement towards Eurasia.

About 39-25 Ma ago, during the Oligocene, NW to SE extension started in the Western Mediterranean region which gradually changed direction to SW-NE extension (figure 1.2). This event occurred contemporaneous with a strong reduction of the northward absolute motion of Africa towards Europe. (Jolivet & Faccenna, 2000)propose that this reduction was induced by the collision of the African/Arabian plate with Eurasia, which slowed down the movement of the whole African continent. This caused a change in paleostress, leading to the opening and eastward propagation of basins in the Western Mediterranean. From west to east (and respectively from old to young) the Alboran basin, the Liguro-Provencal basin, the Algerian basin and the Tyrrhenian basin were formed. At the same time, the (oceanic) Adriatic plate subducted westward under the Eurasian plate, creating the Alps and later the Apennines when the direction of subduction changed.(Argnani, 2012; Gueguen, Doglioni, & Fernandez, 1998; Vignaroli, Faccenna, Jolivet, Piromallo, & Rossetti, 2008; Carminati and Doglioni, 2012).

From 25 to 10 Ma, the Apennines front rotated 60 degrees counterclockwise while still migrating eastward (Channell, 1992; Muttoni et al.,2013). Due to this rotation the length of the

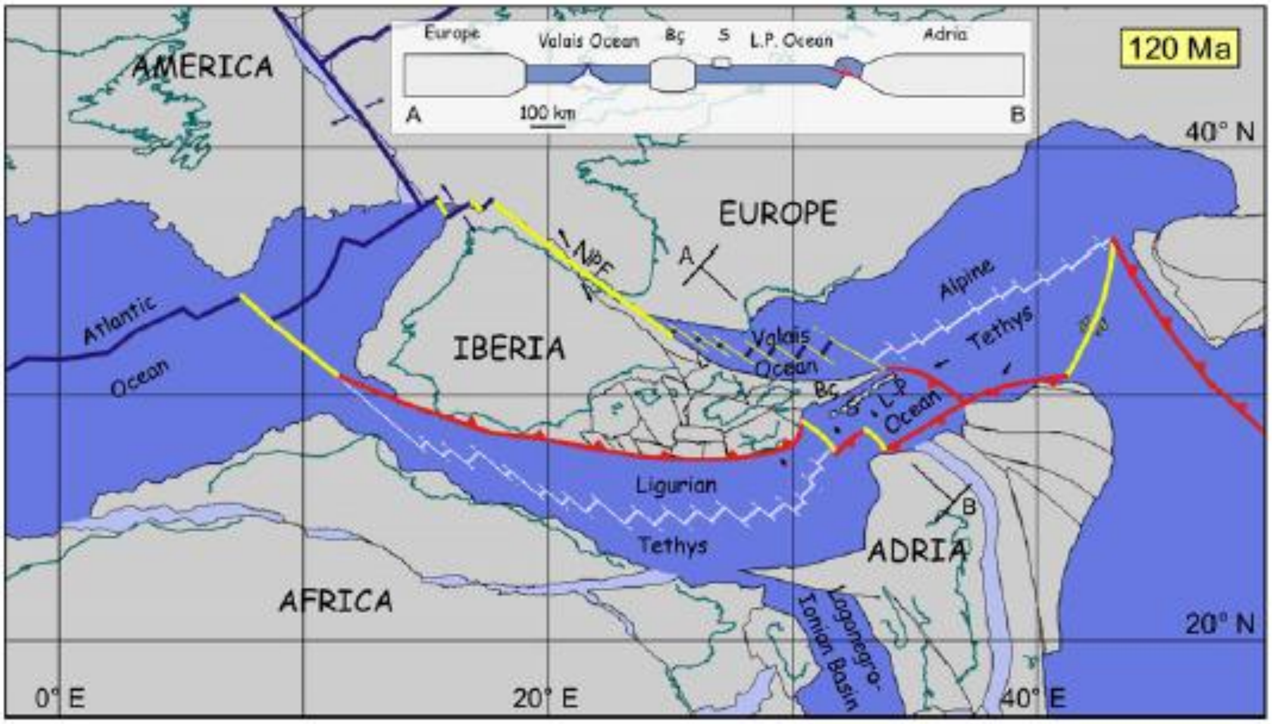

Figure 1.1: Turco et al,. 2012. 'Plate reconstruction of the western Tethyan region at 120 Ma (early Aptian). The distribution of the continental lithosphere is shown in gray. Present-day coastlines are shown for reference. Areas affected by thinning are shown in light blue. Black arrows represent direction and magnitude of relative motion. Strike–slip faults are shown in yellow. Red lines are convergent boundaries. Blue lines are spreading centers. White lines represent extinct spreading centers. L–P: Liguro–Piemontese Ocean; NPF: North Pyrenean Fault; S: Sesia Zone; Bç: Briançonnais Domain.'

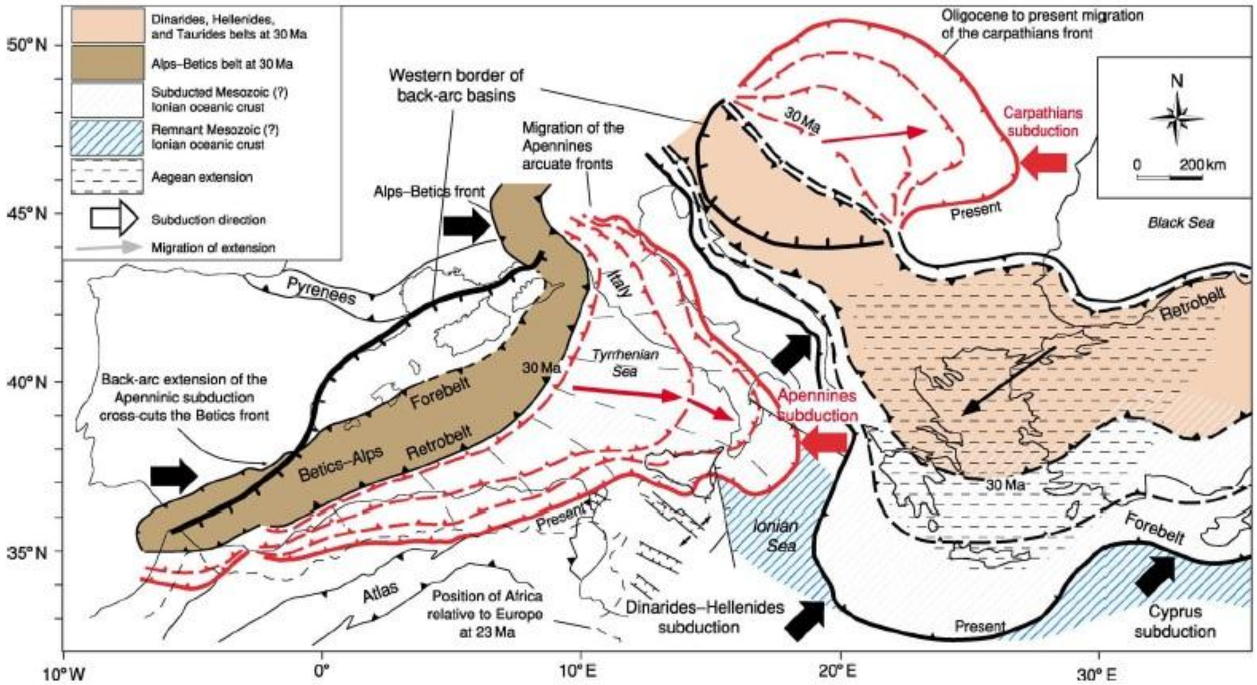

Figure 1.2: Carminati and C Doglioni, Mediterranean tectonics 2005. p. 142
'Main tectonic features of the Mediterranean realm, which has been shaped during the last 45Ma by a number of subduction zones and related belts: the double-vergent Alps–Betics; the single eastwards-vergent Apennines–Maghrebides and the related western Mediterranean back-arc basin; the double-vergent Dinarides–Hellenides–Taurides and related Aegean extension; the single eastwards-vergent Carpathians and the related Pannonian back-arc basin; and the double-vergent Pyrenees.'

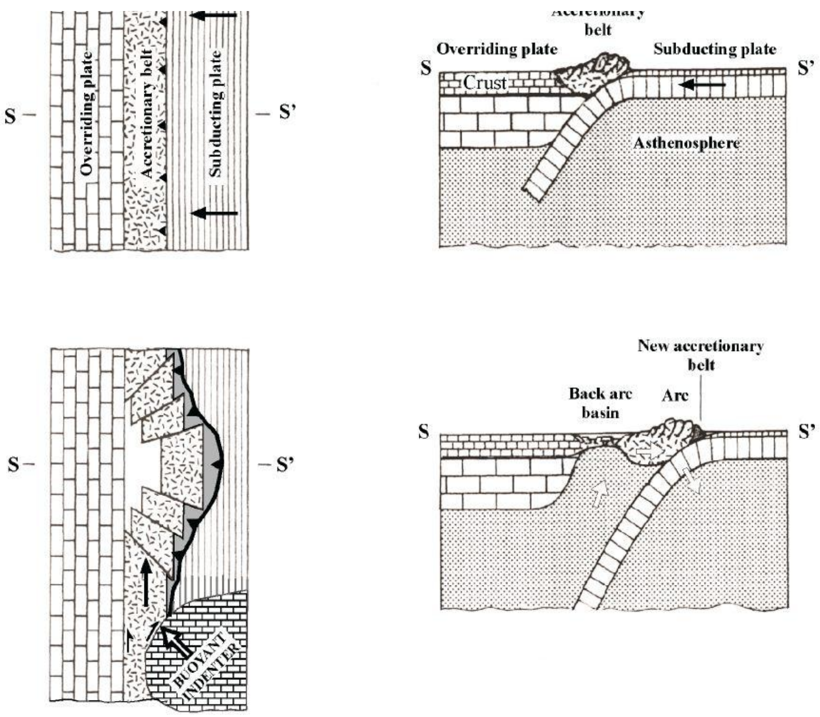

Figure 1.3: Mantovani et al., 2001 Extrusional back-arc extension: *'a sector of the accretionary belt is deformed by an extrusion mechanism and partly separates from the overriding plate. This separation is accommodated by crustal stretching in the back arc zone. Simultaneously, the outward migration of the deforming belt (arc) causes the roll back of the slab lying in front of it.'*

Apenninic arc increased, which led to the break-up of the arc between the Balearic Island and Sardinia. Also during this time the Tyrrhenian basin started to open (Gueguen et al., 1998).

Around 10 Ma the Liguro-Provencal basin had almost completely opened. The Vavilov basin progressively reached the oceanization stage. (Gueguen et al., 1998)
Around 5 Ma the Apenninic slab started to split in two sub-arcs. This was caused by a major strike-slip fault and two different roll-back rates over this fault; In the southern Apennines the migration of the subduction hinge halted while in the central and northern Apennines the roll-back of the subduction hinge continued (Gueguen et al., 1998).

The extensional regime close to the subduction zone can be explained by a process called back-arc extension (Figure 1.3). Several theories for this mechanism include slab pull, corner flow, sea anchor and extrusion (Mantovani, Viti, Babbucci, Tamburelli, & Albarello, 2001; Nakakuki & Mura, 2013); with reference to Uyeda and Kanamori, 1979; Taylor and Karner, 1983; Tamaki and Honza, 1991; Taylor, 1995; Mantovani et al., 1997, 2000a; Flower et al., 2001). According to Mantovani,back-arc extension *'is expected to occur along a consuming border where a sector of the accretionary belt is deformed by an extrusion mechanism and partly separates from the overriding plate. This separation is accommodated by crustal stretching in the back arc zone. Simultaneously, the outward migration of the deforming belt (arc) causes the roll back of the slab lying in front of it.'* (Mantovani et al., 2001)
This explanation seems the most reasonable, especially in the case of the Mediterranean, where back-arc extension seems to occur mostly in arcs with a significant curvature (Uveda & Kanamori, 1979; Heuret et al., 2007; Clark et al., 2008).

2. Lithostratigraphy

The lithostratigraphy in the Monte Sibillini area is represented by the Umbria-Marche succession, which consists entirely of sedimentary rocks (figure 2.1).

As mentioned before, in late Triassic times Pangea started to break up. Due to this rifting phase a marine transgression followed. This shallow water environment resulted in the formation of the Anidriti di Burano Fm, a thick succession (1-2km) of carbonate-evaporites deposits at the base of the Umbria-Marche succession (Di Naccio et al., 2005).

In early Jurassic times, an environmental change resulted in the beginning of carbonate sedimentation in the area that was subjected to late Triassic extension (Muttoni et al., 2013). In early Liassic times the first carbonate deposits that are present in the Monte Sibillini area were formed, namely the Calcare Massiccio Fm: a thick-bedded, whitish limestone succession consisting mostly of biomicrite (Di Naccio et al., 2005). The thickness of the Calcare Massiccio varies between 600 and 800 meters, due to synsedimentary normal faults. During the entire Jurassic the area remained subjected to extension, causing normal faults to create horst and graben structures that controlled deposition (Di Naccio et al., 2005).

On the structurally higher horsts, shallow water carbonates developed, until drowning of the carbonate platforms occurred. Then condensed successions developed on the heights, whereas complete successions developed in the grabens (Guerrera, Tramontana, Donatelli, & Serrano, 2012). The condensed type is characterized by sub-tidal to supra-tidal carbonates and shows hiatuses over time. The complete succession is composed of the Calcare Massiccio Fm, the Corniola Fm, the Bosso Fm, the Sentino Fm and the Calcari Diasprigni Fm respectively (Marchegiani, Bertotti, Deiana, Mazzoli, & Tondi, 1999).

During the Early Cretaceous rifting had ended and the Maiolica Fm. was deposited, smoothing out the irregularities in the Jurassic seabed. In the Maiolica Fm., variations in thickness are visible due to the deposition on the irregular seabed (Mazzoli, Pierantoni, Borraccini, Paltrinieri, & Deiana, 2005).

From the Aptian age on, more marls and shales were deposited, resulting in the Marne a Fucoidi Fm and the consecutive Scaglia formations. Towards the top of this last formation a higher amount of clay is visible, resulting in more marly limestones like the Scaglia Variegata Fm. Due to moderate tectonic activity during the Eocene, gravitational deposits occured in the upper member of the Scaglia Rossa and the Scaglia Variegata Formations (Guerrera et al., 2012).

In the Lower Miocene, volcanic activity resulted in the occurrence of some volcaniclastic material. This is deposited amongst mainly marls in the Bisciaro Fm. Also in the overlying Schlier Fm some diluted volcanogenic materials can be recognized, although the formation is characterized by hemipelagic lithofacies.

Umbria-Marche Succession
Source: Drops of Time, A. Montanari et al, 2002

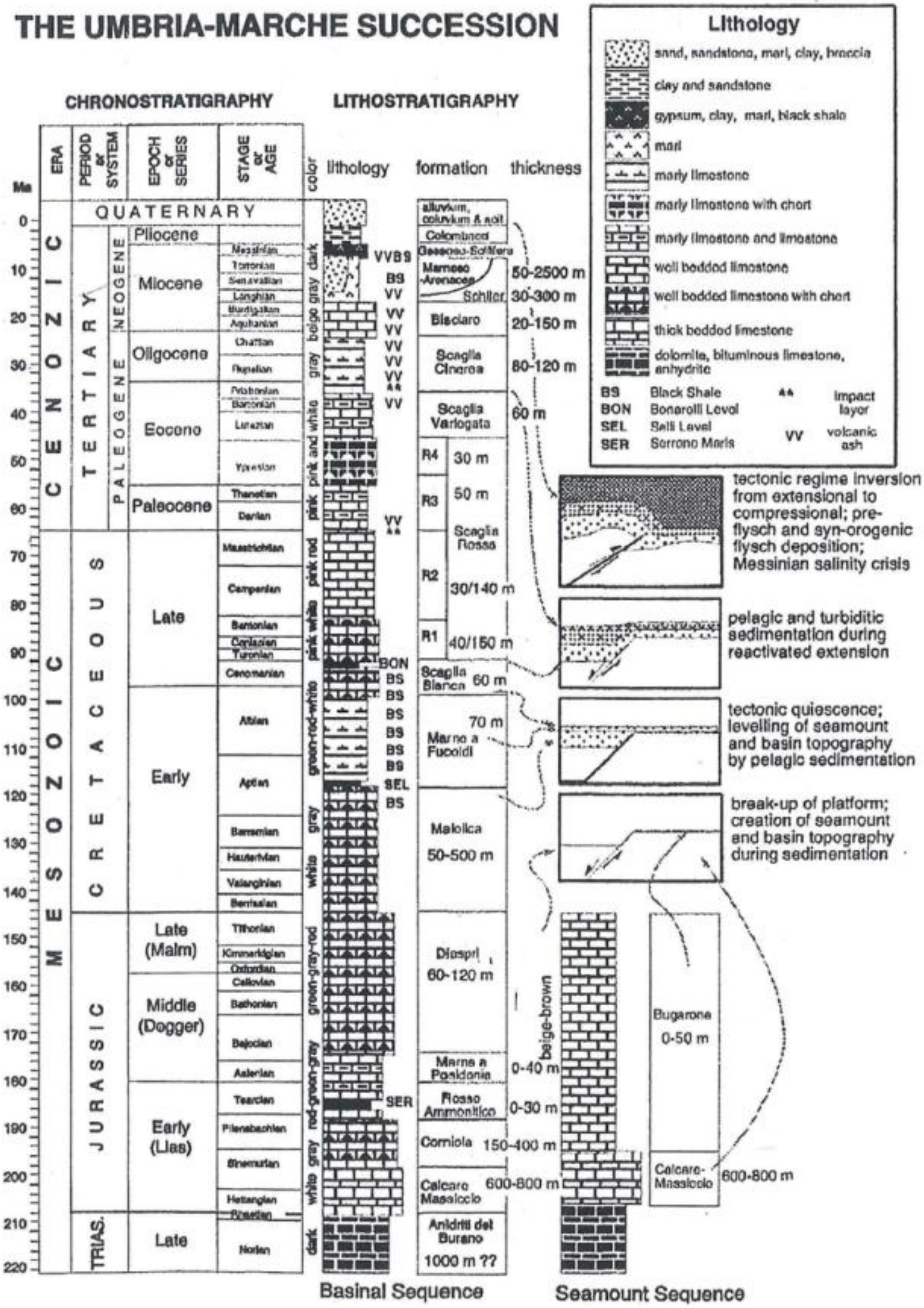

Figure 2.1: Lithostratigraphical column

The deposition of the Schlier Fm is typically followed by siliciclastic turbiditic successions, including the Formazione della Laga. The supply of siliciclastic material indicates the onset of a foredeep stage (Guerrera et al., 2012; Muttoni et al., 2013).

Turbidites

Extensive outcropping turbidites were found near Pievebovigliana (Appendix E: group 24). As for the lithology of the turbidites, apart from carbonate clasts, siliciclastic clasts were also found. Since the Apennines are composed solely of carbonates, the turbidites must have been of a foreign origin. Most probably these turbidites have found their origin in the Alpine belt. Apart from this, several lumps of mudstone of about 10 cm in diameter have been found inside the turbidites. These mudstones have probably found their origin in the older calcareous formations, like the Maiolica Fm.

Diasprigni unconformity

An unconformity between the Calcare Diasprigni Fm. and the Maiolica Fm. was discovered (figure 2.2). (Deiana & Centamore, 1986) and (Deiana et al., 2002) also propose an angular unconformity between the Diasprigni and Maiolica formations. This unconformity is part of a facies change in which the Bugarone Fm. devolves into the Rosso ammonitico Fm., the Calcari a Posidonia Fm. and the Calcari Diasprigni Fm. This can be seen in Appendix B.5.

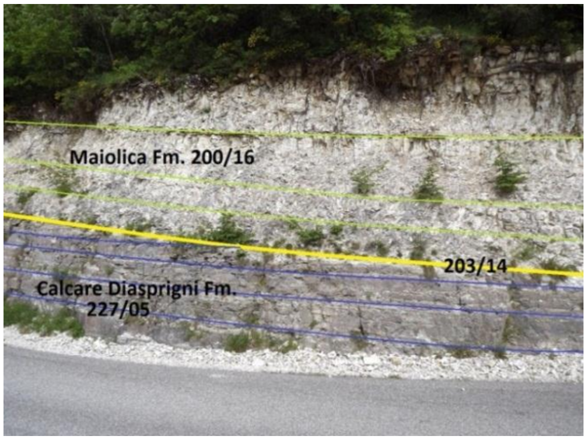

Figure 2.2: Diasprigni-Maiolica angular unconformity in a corner of the Strada Provinciale 91. The lower formation is the Calcare Diasprigni Fm., the upper formation the Maiolica Fm.

3. Structural geological features of the Sibillini area

The geological data presented in this paper have been acquired through a detailed analysis of outcrops and the reconstruction of several cross-sections through the 'Fiume Fiastrone valley'. A structural map and a large SW-NE cross-section through this valley are presented in figures 3.1 and 3.2 to give an overview of the area and a general idea of the geology before reading the subsequent subchapters in which structural geological highlights will be discussed.

3.1 The Sibillini thrust

The Sibillini thrust is part of a larger NE-moving fold and thrust belt that is characteristic of the Apennines. The thrust comes to surface in the Fiume Fiastrone valley, just west of the village of Monastero as depicted in figure 3.3 (p.8). The picture shows the older Maiolica Fm. overriding the younger Scaglia Rossa Fm over a 230/35 fault plane. In the hanging wall a minor thrust and two normal faults that were created later can be identified.

Near the thrust face that separates the Maiolica Fm. from the Scaglia Rossa Fm. fault breccia has been observed. The breccia involved clasts from both formations. Red (Scaglia Rossa) and grey (Maiolica) colored spots near the fault zone shown in fig. 3.3 also indicate severe deformation that might include fault breccia. No clear trend in the fractures near the fault zone could be observed.

Thrusting has caused the formations on the hanging wall to overturn (Appendix C.2). The axial plane of the overturned anticline on the north side of the valley was measured to be 230/34. This shows that the fault plane and axial plane of the overturned anticline are nearly identical.

Vertical displacement was determined by taking the difference in stratigraphical succession between the middle Maiolica Fm. and lower Scaglia Rossa Fm., which is about 320 meters(Montanari et al., 2002; Deiana,. 2002). The orientation of the fault plane was measured to be 230/35 as can be seen in scross-section 3 (Appendix B.3). Since the fault is thought to gradually become horizontal as it approaches the detachment horizon, it is essential to know the course of the dip in order to determine lateral shortening. Lateral shortening can be calculated by rearranging the tangent rule:

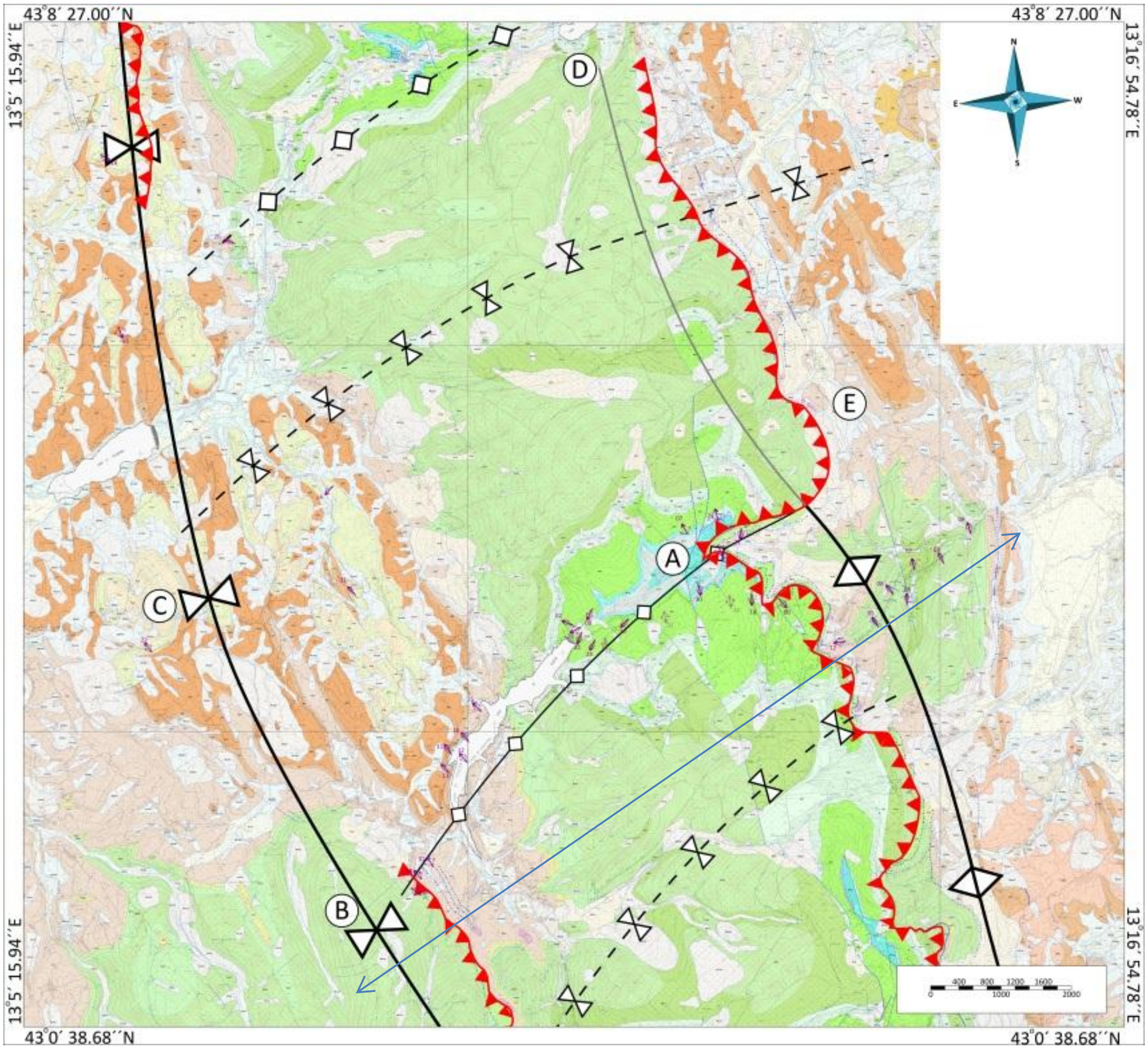

Figure 3.1 Structural overview of the Sibillini Area: Generally two folding orientations and one major thrust; more detailed structural map in appendix A

A: Highest point of the dome structure. However, this is not the top of the dome.; B: Location of expected horseback structures. C: Location of expected bathtub structures. D: In grey: Continuation of anticline caused by SW-NE directed shortening. The hinge of the anticline and the main thrust fault seem to more or less coincide. E: The main thrust is folded (NW-SE directed shortening).

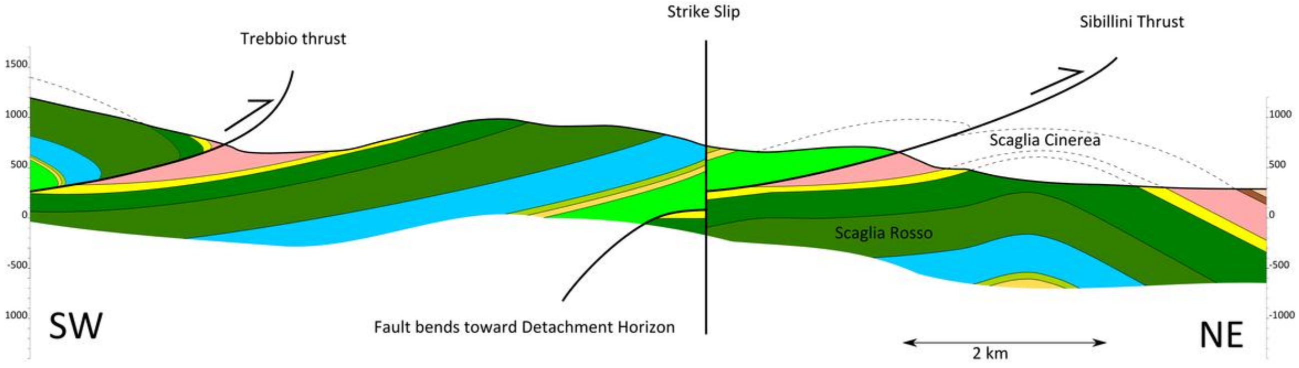

Figure 3.2 SW-NE cross-section along entire fiume fiastrone valley, exact position in fig 3.1

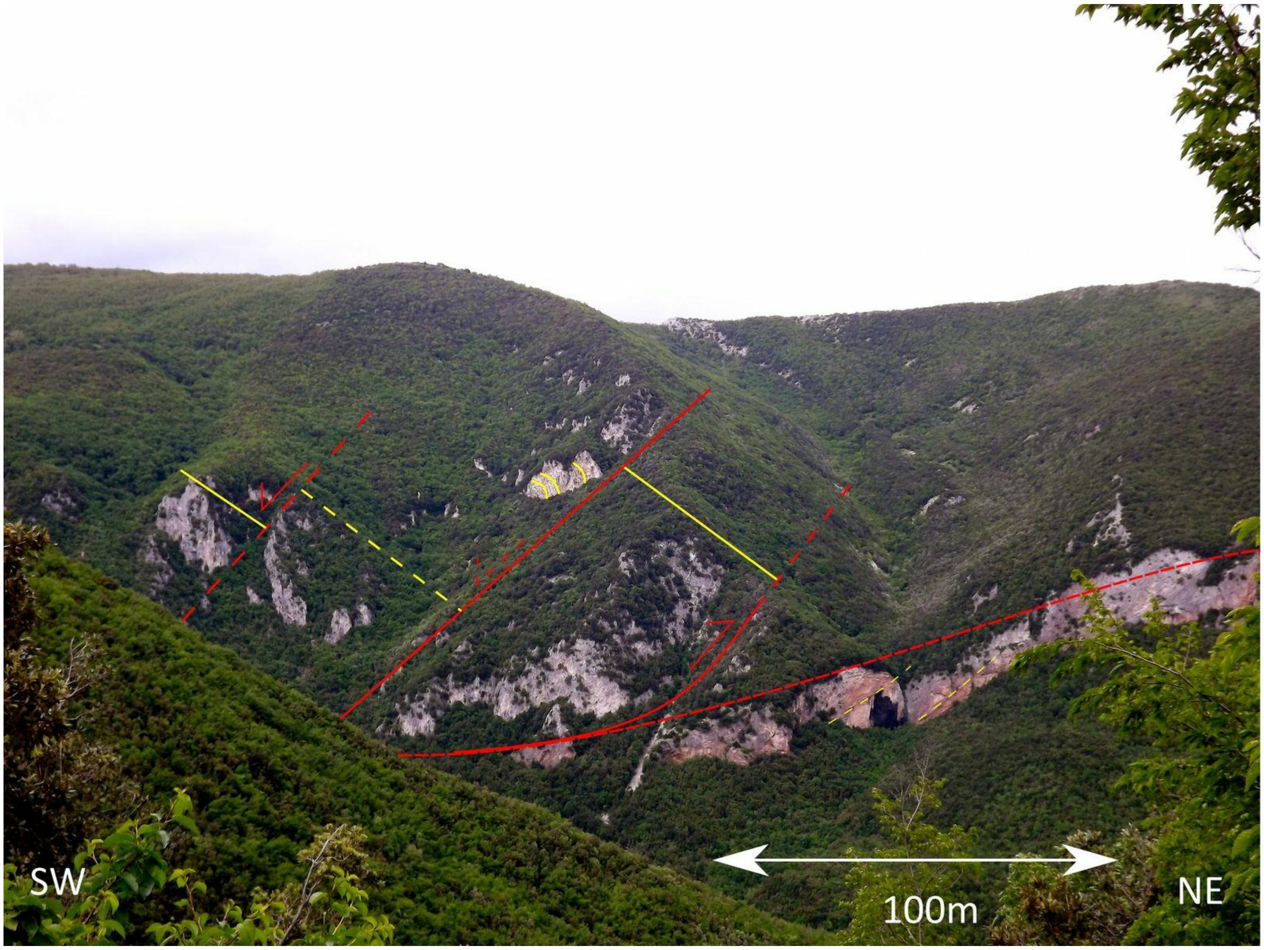

Figure 3.3 Outcrop of the main thrust fault. Fault planes are depicted in red, bedding is depicted in yellow. A thrust and two normal faults split of the main thrust fault. The transport direction of the middle fault (normal fault) is based on the difference in lithology in the upper part of the outcrop (curved yellow lines). However, this appears to be a fresh outcrop in comparison with the description by Calamita (Calamita, Satolli, & Turtù, 2012), and an alternative interpretation is that the difference in color is due to lack of weathering. The curved bedding lines in this part of the outcrop could an effect caused by drag of the main fault.

$$lateral\ shortening = \frac{vertical\ displacement}{\mathrm{TAN}(average\ dip\ angle\ of\ fault)}$$

Based on data acquired throughout the valley, a cross-section was constructed in which the average dip of the fault was determined to be 10 degrees. This corresponds to roughly 1800 meters lateral shortening, which is a plausible amount with regard to the 6,5 km spacing between the two thrusts in the valley.

It is proposed by (Massoli, Koyi, & Barchi, 2006) that there are two possible detachment horizons in the Umbria-Marche lithostratigraphy: the shallow and very soft Marne a Fucoidi Fm. and the deeper Anidriti del Burano Fm. (Triassic evaporates). The Sibillini thrust has certainly not slid across the Marne a Fucoidi Fm. (FUC) because the FUC has been deposited on top of the Maiolica Fm., which was itself moved by the thrust. Hence it is plausible that the Anidriti del Burano Fm. formed the décollement. A similar thrust fault with overturned Scaglia Rossa was observed near 6,5 km westward, near Trebbio as can be seen on the geological map (Appendix D).

3.2 Dome structure

The second most important geological structure in the Monte Sibillini area is an asymmetric dome (figure 3.1: perpendicular fold axes). This dome has a general long side that runs SW-NE and a short side that runs NW-SE, parallel to the strike of the Apennines. The dome is roughly 6.5 kilometers long, measured from anticline to syncline along the smooth side of the dome (from A to B, figure 3.1). However, the dome is locked in between two thrusts and is presumed to have a shorter, steeper side NE

(Tavarnelli, 1997). The dome is roughly 3-4 kilometers wide, measured (again) from anticline to syncline (figure 3.4, distance between B and syncline near C). It appears to be roughly symmetric with respect to the next syncline further SE (near point D).

The long side of the dome has a curvature (figure 3.4, A to B); the dome seems to bend from SW to SSW more eastward in the area, near the lake of Fiastra. However, no evidence has been found that this curvature also occurs in NW and SE direction of the dome (figure 3.4, assumed anti-/synclines) are depicted by striped lines). The next clearly visible dome appears some ten kilometers to the north, at the Lake of Caccamo, although smaller domes and horse-back structures may exist in between the two lakes. Clues for smaller domes are found (i.e.) north of Monte Codardo, where the Maiolica Fm. outcrops. Bathtub (figure 3.4, C) structures are expected in the southwest of the area; however, no sustainable evidence for this assumption has been found.

As mentioned above, the main dome in the Monte Sibillini area seems bounded by two thrust faults. However, the anticline striking parallel to the Apennines appears to have a fold axis underneath the main thrust (figure 3.4E, Appendix B4) This means that the anticline itself has been shortened by roughly 1800 meters, giving a total estimate for the length of the dome of 8.3 kilometers. (figure 3.3, 3.4, Appendix B7)

Generally, data have been collected around the anticlinal axis of the SW-NE striking fold (Figure 3.4, A to B). As a result, the data give some information on the course of the anticline: west of the western thrust there is a general fold axis of 124/04 (Appendix C.1a), while the fold axis between the thrusts is 145/00 (Appendix C.1b) and the fold axis east of the second thrust is 337/06 (Appendix C.1c). This means that the strike varies from west to east from 034-214 to 055-235 to 067-247. This is supported by the fold axis as seen on the map, and provides extra evidence that the dome has about 33 degrees curvature.

3.3 Microfolds and related fracture patterns

Throughout the entire Sibillini area numerous microfolds have been observed on both sides of the thrust fault. Due to the shortening in the Neogene (Gaetani, 2010), lots of minor structures were formed with geometries and orientations consistent with the average NNW-SSE trend of the larger-scale fold-and-thrust belt. These minor structures can be placed into a sequence with three main stages: 1) layer-parallel shortening; 2) folding and 3) thrusting (figure 3.2) (Tavarnelli, 1997; Horne and Culshaw, 2001). This sequence was (partly) found in several outcrops in the Monte Sibillini area. In this paragraph the first two stages are discussed.

The first structural stage of shortening is represented by pressure solution surfaces that formed perpendicular to the bedding, parallel to σ3. They were found in outcrops from group 13 (Appendix E). These pressure solution surfaces, also called stylolites, always form perpendicular to the main stress direction, which in this case was directed perpendicular to the horizontal bedding.

In the second stage, microfolds began to form, ranging in both amplitude and wavelength from several centimeters to meters. These folds, that were very clearly visible at waypoint 189 and group 13, have mostly a concentric geometry and range from angular (chevron folds) to curvilinear (figure 3.4). All hinge lines of the microfolds found in the Monte Sibillini area show strikes that range between 300 and 350° and thus correspond to the general NNW-SSE trend (Appendix C.3). Within the bedding of these microfolds a different stylolite pattern is visible: in the fold limbs the pressure solution surfaces are oblique to the bedding, whereas in the fold hinge the stylolites appear perpendicular to the bedding (figure 3.5).

Figure 3.4 Chevron fold near waypoint 222 along the Strada Provinciale 91.

Figure 3.5: stylolite pattern (red) at waypoint 223 along the Strada Provinciale 91.

The bedding-cleavage angles in the fold limbs are 40 – 70°. This cleavage pattern is most likely the effect of a bedding-parallel shear towards the fold hinges (figure 3.6b) (Tavarnelli, 1997). Striations that were found on the shearing planes between the layers also indicate this theory.

Late in the second stage, nearing the third stage, the folds began to tighten. This process caused reactivation of the stylolite surfaces (bedding parallel, formed during diagenesis) in the steep limbs of the fold (Horne and Culshaw, 2001).

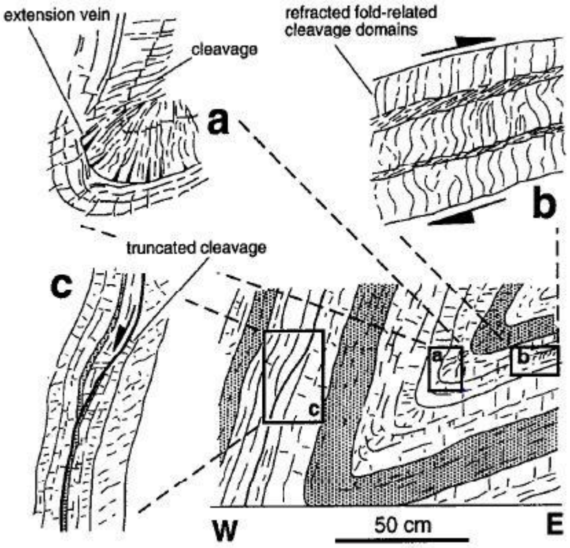

Figure 3.6: Tavernelli, 1996 'Minor structures developed during fold initiation(sub-stage B1). (a) convergent cleavage fans and outer arc radial extension veins in fold hinges. (b) Cleavage refraction phenomena in alternating limestones and marls. (c) Minor contraction faults off-setting cleavage as a consequence of flexural-slip.'

3.4 Strike-slip faults

Strike slip faults represent a transport direction and, according to Van der Pluijm a mean stress direction. Therefore strike-slip fault systems could be a major indicator of occurring stress regimes. (Van der Pluijm & Marshak, 2004).

Large scale strike-slip faults

Based on the map created by (Sarti, 2003), there are roughly six groups of strike-slip faults, based on orientation and movement direction (Appendix A). Besides these six groups there are also some faults that do not belong to a group and seem rather randomly distributed. Notably, there is only one group of sinistral strike-slip faults, while the rest of the groups all represent dextral faults (Appendix G; dextral movement is represented by shades of purple, sinistral movement by shades of brown).

However, these dextral groups range over 180 degrees and do not have a dominating direction. The sinistral group has a strike of N-NNW, and does not appear to form a conjugate set with any of the other sets of faults. This sinistral set is, however, in accordance with large sinistral transcurrent faults found more south, and suggest a NW-NNW striking direction of compression (Bonini, Sani, Moratti, & Benvenuti, 2011).

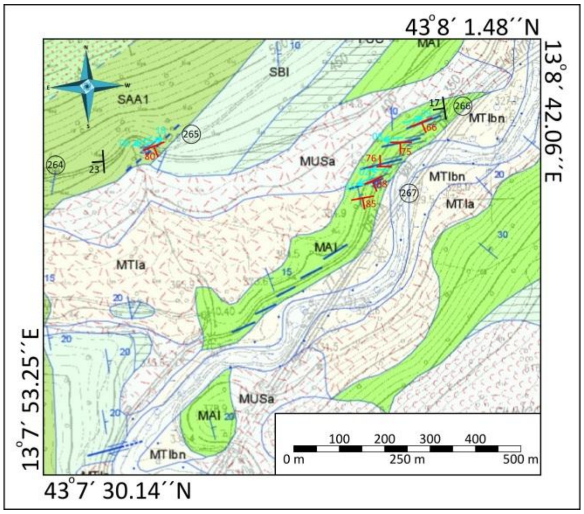

Figure 3.7 Map of dextral strike-slip system, found in the northern part of the area. Striations are indicated in light blue, measured fault planes in red. Faults by Sarti are depicted in dark blue (Sarti, 2003). Faults show a left-stepping dextral strike-slip system.

Minor strike-slip faults

Only a few strike-slip faults are available for direct measurement. These faults are minor faults and do not show much displacement. Out of the outcrops available, the most informative was found between waypoint 266 and 267 and nearby waypoint 265 (in the North of the area, Appendix D; figure 3., 3.9 and 3.10). Here a set of vertical to subvertical, dextral faults can be found with a strike of 080-260. The faults show a left-stepping en-echelon pattern, with only horizontal to subhorizontal movement along the fault. The mean direction of displacement is towards 080, along the fault plane, although this is mostly due to one measurement that has a deviant direction (074/39) (Figure 3.8). Without this measurement the mean transportation direction would be towards 261/07, which is a more reasonable estimate with respect to the fault and striations measured at waypoint 265 (Appendix D, Geological Datamap).

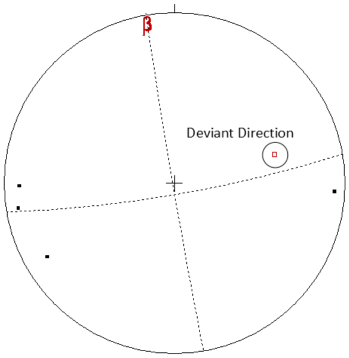

Figure 3.8
Stereoplot of striations of strike slip faults around waypoint 266.

In the main profile (Appendix B1 to B4, see also figure 3.7 and 3.8, 'South') there are even less striations visible than in the northern part. There are only four measurements, where the fault planes are again vertical to subvertical and the striations horizontal to subhorizontal. In this part there are no indications of the direction of movement, and one out of the four measurements (waypoint 126) is taken in an area in which there appears to be no system at all. However, if this waypoint is left out, the mean striations dip toward 146/08 and the mean fracture plane is 242/88, meaning that the strike would be roughly 150-330. This could mean that there is a conjugate set of strike slip faults; the northern set is orientated (roughly) 80-260 while the southern set is directed 150-330. This is a difference of 70 degrees, a reasonable difference for a conjugate set.

The angle between the two main directions, found in the North and in the South respectively, is about 65 degrees (figure 3.11, next page). The northern faults show a dextral movement, which fits with a conjugate set. Although there is no evidence for any direction of movement in the southern part the area, the conjugate set suggests that this movement could be sinistral. If this is the case, the set would indicate that σ1 is roughly orientated WNW-ESE and σ3 is roughly orientated SSW-NNE. Since this direction for σ1 is not perpendicular to the orientation of the Apennines, it suggests that in the final stages of deformation the stress regime has turned more SE-NW, and that it is now slightly oblique. This stress regime could have also caused the dome structure (see Chapter 3.1).

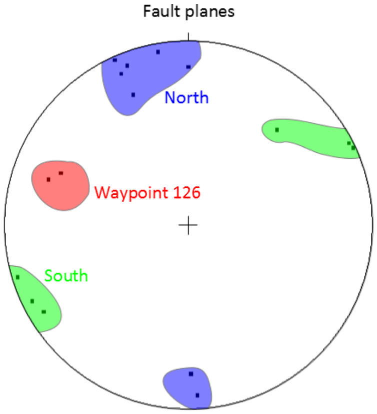

Figure 3.9: Stereoplot diagram of strike-slip faults, fault planes.

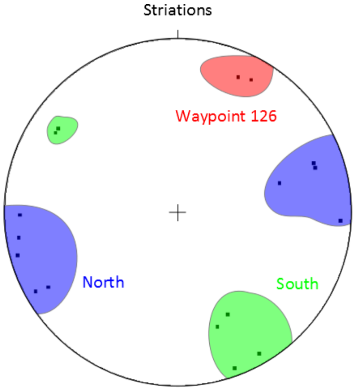

Figure 3.10: Stereoplot diagram of strike-slip faults, striations.

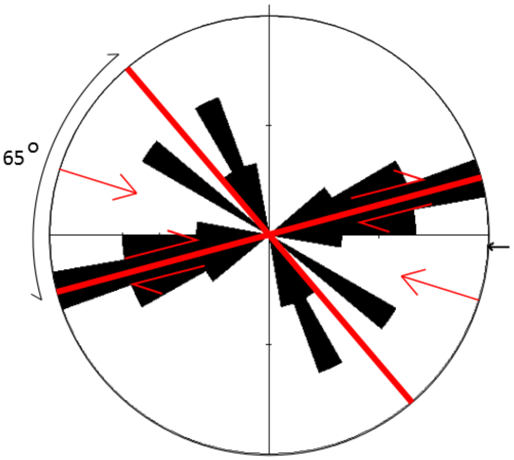

Figure 3.11: Rose-diagram of the striations as found on fault surfaces. Striations record the last stages of deformation and can give an indication of the final stress regime. The movement of the faults in the north of the area is shown by half, red arrows, while the main stress direction is shown as a full arrow. The angle between the two main faults is roughly 65 degrees.

3.5 Normal faults

Many normal faults were found in the Scaglia Rosso fm., in the footwall of the fold and thrust belt. Only in group 8, 9 and 10 there is a sufficient amount of data for statistical analysis of these faults. Here the dominant direction of extension is N219E (figure 3.12A), which is roughly equal to the shortening direction of the main thrust. It has to be noted though, that variance is about thirty degrees in all directions and that in a plot of all measured faults, there appears to be no definable system (figure 3.12C). However, if the measurements with a dip higher than 70 degrees are left out (figure 3.12B and 3.12D) (assuming here that these cannot be normal faults, but must rather be strike-slip faults) the result of this analysis is a dominant direction of N211E, which is compatible with the earlier found direction of N219E.

The presumed strike-slip faults that have been left out should fit in with earlier found strike-slip measurements. When the left-out faults are added to the strike-slip fault system (figure 3.12E and 3.12F), the strike-slip system is lost. This means that these faults do not fit in one of the known systems.

Hence no hard conclusions can be drawn and this normal fault system. The variance in dipping directions may only be considered a small clue that these are reactivated faults that originate from Early Jurassic times when the Calcare Massiccio was deposited in an SW-NE extensional regime (creating horsts and grabens).

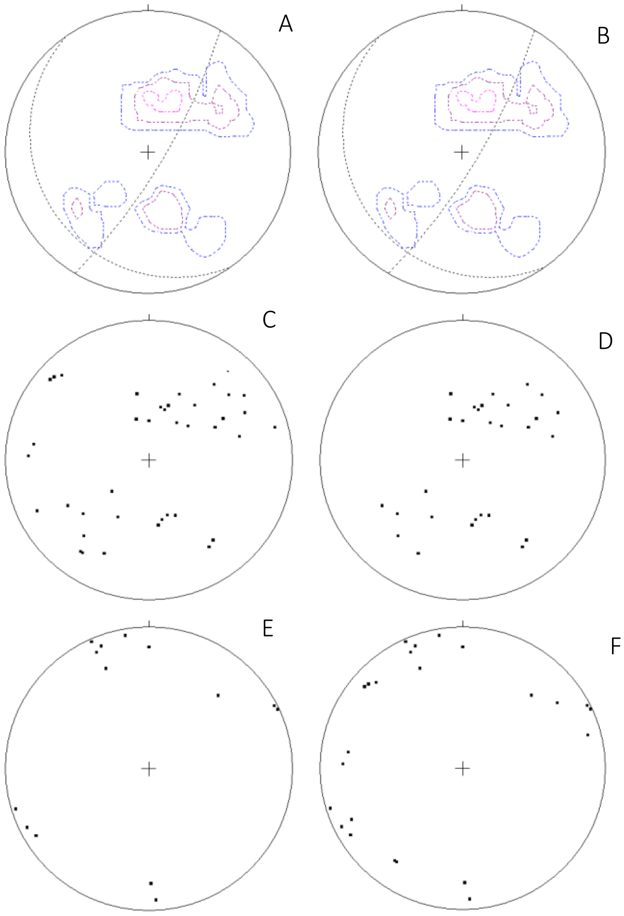

Figure 3.12 Stereoplots of fault planes. Dashed, colored lines represent point density. Black dashed lines represent calculated girdles.
A: Group 8, 9 and 10; B: Normal faults without 70+ dip; C: All faults (including 70+); D: Normal faults without 70+ dip; E: All strike slip fault planes that contain striations; F: same as E with the added measurements that have been left out of the normal fault analysis.

3.6 Structural implications of turbidites

In the late Miocene siliciclastic turbiditic sequences were deposited, as already mentioned in the lithostratigraphy.

The average orientation of these outcropping turbidites is 330/22, this strike differs approximately 90 degrees with the surrounding older formations. The orientation of the older formations is thought to be due to an ENE-WSW directed principal stress direction that also created the dominating fold-and-thrust belt of the Apennines.

The turbidites could be located in the hinge area of a syncline which dips to the North-West. This would mean that this syncline was also under influence of a different principal stress than the ENE-WSW compressional regime. This is in correspondence with a shift in the Apenninic stress regime during the late Tertiairy and early Quaternary (Speranza, Mattei, Naso, Di, & Corrado, 1998) and (Bonini et al., 2011).

Furthermore, no significant change in the orientation along the outcrop was measured. Also, an unconformity could be seen at waypoint 310 (Figure 3.13). The two above mentioned facts indicate that the turbidites are post-rifting deposits.

Figure 3.13: Unconformity surface bounded by turbidites of different age.

4. Interpretation and discussion

The geology in the area around the Fiume Fiastrone valley is controlled by a NW-SE striking fold and thrust belt (parallel to the Apennines) that finds its origin in the westward subduction of the Adriatic plate underneath the Eurasian plate.

The main structure in the Monte Sibillini area is two thrust faults that enclose a dome with a 6.5 km SW-NE oriented long axis and a 3-4 km NW-SE oriented short axis. One of the thrusts crops out west of Fiastra, the other west of Monastero. Both thrusts show a similar geometry: a ramp and flat structure with a décollement in the Anidriti del Burano Fm. and an overturned anticline on the hanging wall. Also, both thrusts have a transport direction towards NW. The vertical displacement is about 320 m, with a lateral shortening of 1800 m.

Apart from the major dome and the thrust structures many microfolds and minor faults were found that are also associated with SW-NE compression. These minor structures are part of the deformation sequence proposed by Tavarnelli (Tavarnelli, 1997) (Figure 4.1, next page). The fracture patterns related to flexural slip observed by Tavarnelli are present in the microfolds in the Monte Sibillini area.

Several clues have been found that indicate a principal stress perpendicular to the one that formed the Apenninic fold-and-thrust belt. Firstly, to the west of the Monte Sibillini area, turbidites have been found with an average strike of 330°. We propose that these turbidites are located in the hinge area of the NW dipping syncline. If so, a second deformation phase must have caused the dipping of this syncline. Secondly, the dome itself is an indication of two stress regimes. If this second deformation phase was younger than the first one that created the fold-and-thrust belt, the second deformation phase must also have deformed the thrusts. However, no evidence was found that the thrust near Monastero or the thrust near Fiastra is deformed by a second stress regime. Thirdly, strike-slip faults have been found that indicate a WNW-ESE directed principal stress.

Shortening that occurred in NW-SE direction was 300 m over a 6 km section (Appendix X, cross-section 6, 6300m arc length vs. 6000m cross section). If a second deformation phase started in the late Pliocene and Quarternary (the last 3 Ma), that would correspond to roughly 0.1 mm of shortening per year, which seems a reasonable shortening rate.

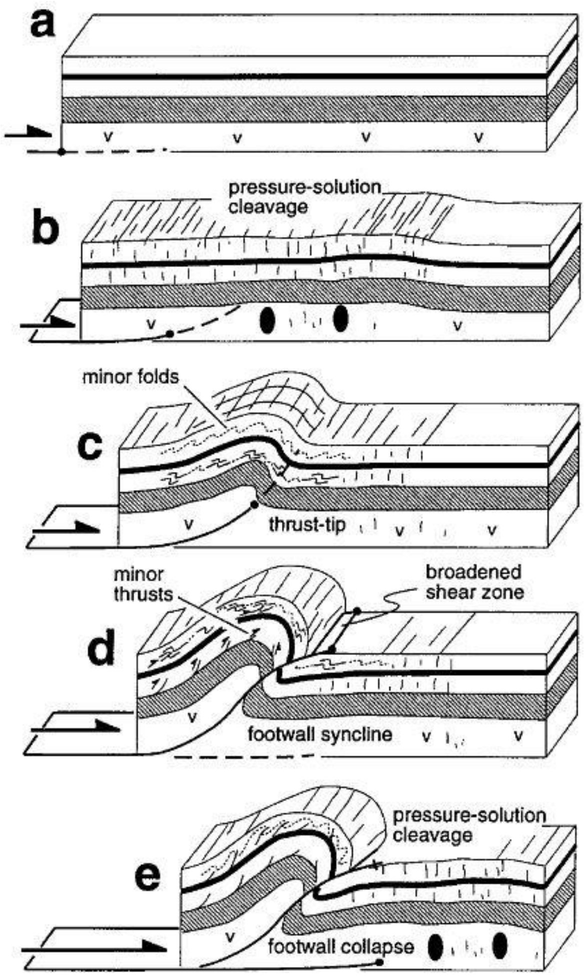

Figure 4.1. Tavarnelli 1996 'Kinematic deformation model (a-e) in time for the Umbria-Marche sedimentary cover (grey and black layers are the Lower Liassic Calcare Massiccio Fm. And the middle Createaceous Marne a Fucoidi Fm., respectively). The model assumes a progressive character of Neogene compressional deformation, a kinematic link between folding and thrusting (which are interpreted to result from tip-line folding processes), and a hinterland-to-foreland thrust propagation sequence.'

Implications of dome structure

The dome structure has some major tectonic implications; if the dome was created during one tectonic stage, there must be have been force balance in which σ1 and σ2 switch positions. A possible theory of a one-stage stress-regime has been investigated; the "enlarged Riedel Shear" theory (figure 4.2). In this theory the second stress vector is caused by a laterally varying force, causing a force regime as seen in strike-slip faults. However, in this stress-regime certain strike slip faults should be dominant, which is not visible in the Monte Sibillini area, and therefore the theory has been rejected. The only other possibility is that there has been another tectonic stage, which caused a change in the relative orientation of σ1 and σ3. Consequently, this leads to the question which stage was first, NW-SE compression or NE-SW compression (logically assuming here that the main folds are caused by compression). Possible evidence would be lateral movement or thrusts that deform earlier created faults and folds. However, the major outcrop of the Sibillini thrust, at the hinge of the anticline, shows no considerable curvature over a length of about 1 km. Therefore this observation does not confirm the two-stage-theory. It may be possible though that the thrust fault exhibits curvature on a larger scale.

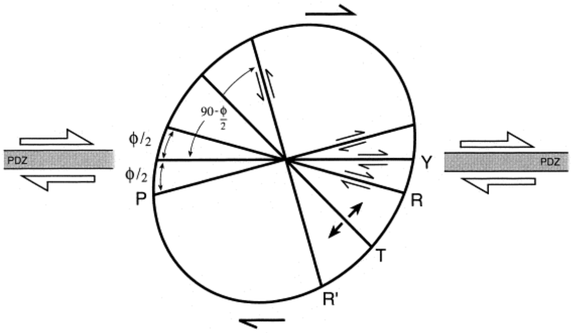

Fig. 4.2
Riedel shear configurations; dextral movement as seen in P should be dominant (Davis, Bump, Garcõâ, & Ahlgren, 2000).

5. Conclusion

It is likely that two deformational phases have sculpted the landscape in the Fiume Fiastrone valley. There is no clear evidence of one phase preceding the other but clues have been found that a NE-SW compressional force preceded a later NW-SE compressional force. This is congruent with a literature study that indicates a Neogene origin of the fold-and thrust belt and Quaternary NW-SE compression (figure 5.1, next page).

Further research is possible by means of seismic sections over the fault zone; especially a NW-SE section would be helpful as it would give further insights on the scale and orientation of the (presumably) second deformational phase, and especially on the deformation near the fault zone.

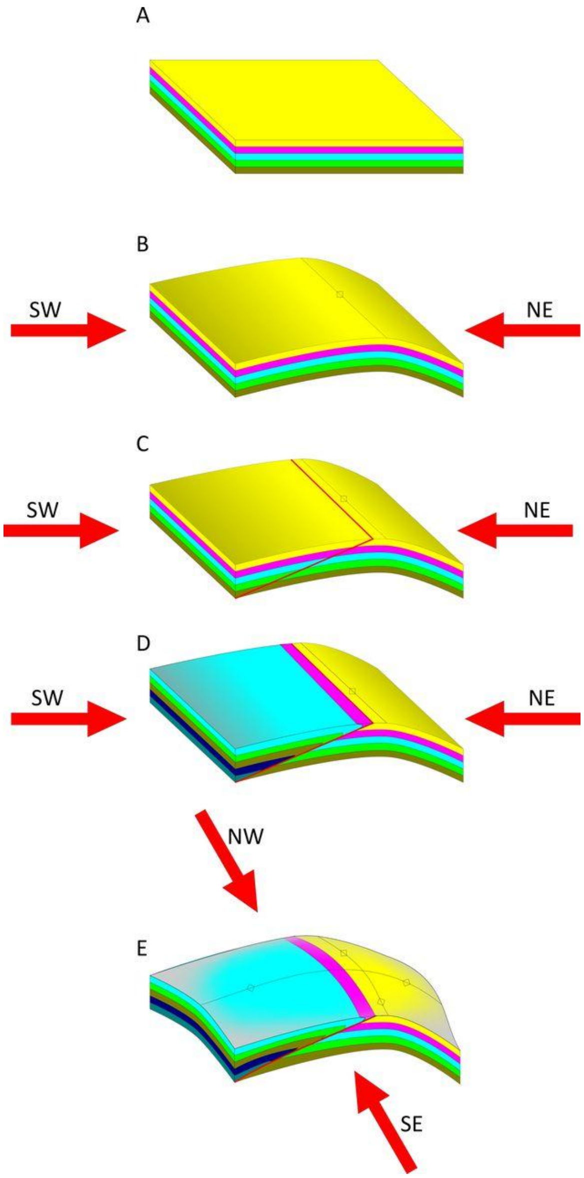

Figure 5.1: Simplified evolutional model of the Fiume Fiastrone geology. A: horizontal formations. B:. initial folding. C: creation of thrust fault. D: development of fold-and-thrust belt. E: NW-SE compression.

Acknowledgements

This work benefited from valuable advice on structural geology from prof. dr. Giovanni Bertotti and prof. dr. Emanuele Tondi. We are thankful for the sponsoring provided by Statoil.

References

Argnani, A. (2012). Plate motion and the evolution of Alpine Corsica and Northern Apennines. *Tectonophysics*, *579*, 207–219. doi:10.1016/j.tecto.2012.06.010

Bonini, M., Sani, F., Moratti, G., & Benvenuti, M. G. (2011). Quaternary evolution of the Lucania Apennine thrust front area (Southern Italy), and its relations with the kinematics of the Adria Plate boundaries. *Journal of Geodynamics*, *51*(2-3), 125–140. doi:10.1016/j.jog.2010.01.010

Carminati, E., Lustrino, M., & Doglioni, C. (2012). Geodynamic evolution of the central and western Mediterranean: Tectonics vs. igneous petrology constraints. *Tectonophysics*, *579*, 173–192. doi:10.1016/j.tecto.2012.01.026

Davis, G. H., Bump, A. P., Garcõâ, P. E., & Ahlgren, S. G. (2000). Conjugate Riedel deformation band shear zones, *22*, 169–190.

Deiana, G. (2002). Tectonic evolution of the external zones of the Umbria-Marche Apennines in the Monte San Vicino – Cingoli area, *Speciale*.

Deiana, G., & Centamore, M. (1986). La geologia delle Marche, Studi Geologici Camerti, *Speciale*, 145.

Di Naccio, D., Boncio, P., Cirilli, S., Casaglia, F., Morettini, E., Lavecchia, G., & Brozzetti, F. (2005). Role of mechanical stratigraphy on fracture development in carbonate reservoirs: Insights from outcropping shallow water carbonates in the Umbria–Marche Apennines, Italy. *Journal of Volcanology and Geothermal Research*, *148*(1-2), 98–115. doi:10.1016/j.jvolgeores.2005.03.016

Gaetani, M. (2010). From Permian to Cretaceous: Adria as pivotal between extensions and rotations of Tethys and Atlantic Oceans. *Journal of the virtual explorer*, *36*.

Giaccio, M. G., Barchi, M. R., Chiarabba, C., & Mirabella, F. (2013). Seismological , geological and geophysical constraints for the Umbria – Tadino fault , Umbria – Marche Apennines (central Italy). *Tectonophysics*, *406*(3-4), 23–29.

Gueguen, E., Doglioni, C., & Fernandez, M. (1998a). On the post-25 Ma geodynamic evolution of the western Mediterranean. *Tectonophysics*, *298*(1-3), 259–269. doi:10.1016/S0040-1951(98)00189-9

Gueguen, E., Doglioni, C., & Fernandez, M. (1998b). On the post-25 Ma geodynamic evolution of the western Mediterranean, *298*, 259–269.

Guerrera, F., Tramontana, M., Donatelli, U., & Serrano, F. (2012). Space/time tectono-sedimentary evolution of the Umbria-Romagna-Marche Miocene Basin

(Northern Apennines, Italy): a foredeep model. *Swiss Journal of Geosciences*, *105*(3), 325–341. doi:10.1007/s00015-012-0118-0

Horne, R., & Culshaw, N. (2001). Flexural-slip folding in the Meguma Group, Nova Scotia, Canada. *Journal of Structural Geology*, *23*(10), 1631–1652. doi:10.1016/S0191-8141(01)00017-7

Jolivet, L., & Faccenna, C. (2000). Mediterranean extension and the Africa-Eurasia collision. *Tectonics*, *19*(6), 1095–1106.

Mantovani, E., Viti, M., Babbucci, D., Tamburelli, C., & Albarello, D. (2001). Back arc extension : which driving mechanism ?, 17–45.

Marchegiani, L., Bertotti, G., Deiana, G., Mazzoli, S., & Tondi, E. (1999). Pre-orogenic tectonics in the Umbria-Marche sector of the Afro-Adriatic continental margin. *Tectonophysics*, *315*, 123–143.

Massoli, D., Koyi, H. a., & Barchi, M. R. (2006). Structural evolution of a fold and thrust belt generated by multiple décollements: analogue models and natural examples from the Northern Apennines (Italy). *Journal of Structural Geology*, *28*(2), 185–199. doi:10.1016/j.jsg.2005.11.002

Mazzoli, S., Pierantoni, P. P., Borraccini, F., Paltrinieri, W., & Deiana, G. (2005). Geometry, segmentation pattern and displacement variations along a major Apennine thrust zone, central Italy. *Journal of Structural Geology*, *27*(11), 1940–1953. doi:10.1016/j.jsg.2005.06.002

Muttoni, G., Dallanave, E., & Channell, J. E. T. (2013). The drift history of Adria and Africa from 280 Ma to Present, Jurassic true polar wander, and zonal climate control on Tethyan sedimentary facies. *Palaeogeography, Palaeoclimatology, Palaeoecology*. doi:10.1016/j.palaeo.2013.06.011

Nakakuki, T., & Mura, E. (2013). Dynamics of slab rollback and induced back-arc basin formation. *Earth and Planetary Science Letters*, *361*, 287–297. doi:10.1016/j.epsl.2012.10.031

Van der Pluijm, B. A., & Marshak, S. (2004). Fractures and Faults. In L. Wiegman (Ed.), *An introduction to Structural Geology and Tectonics* (Second Edi., pp. 321–363). New York: W.W. Norton & Company, Inc.

Sarti, M. (2003). CARTA GEOLOGICA - PROGETTO: “UNICO TERRITORIALE GEOLOGICO” 1:10.000. *Progetto Docup, Ob 5b Progetto Carg*. Retrieved May 15, 2013, from http://www.ambiente.marche.it/Territorio/Cartografiaeinformazioniterritoriali/Archiviocartograficoeinformazioniterritoriali/Cartografie/CARTAGEOLOGICAREGIONALE110000.aspx

Speranza, F., Mattei, M., Naso, G., Di, D., & Corrado, S. (1998). Neogene – Quaternary evolution of the central Apennine orogenic system (Italy): a structural and palaeomagnetic approach in the Molise region, *299*, 143–157.

Stampfli, G. M., Borel, G. D., Marchant, R., & Mosar, J. (2002). Western Alps geological constraints on western Tethyan reconstructions, 75–104.

Tavarnelli, E. (1997). Structural evolution of a foreland fold-and-thrust belt: the Umbria-Marche Italy. *Journal of Structural Geology*, *19*, 523–534.

Uveda, S., & Kanamori, H. (1979). Back-Arc Opening and the Mode of Subduction. *Journal of Geophysical Research*, *84*, 1049–1061.

Vignaroli, G., Faccenna, C., Jolivet, L., Piromallo, C., & Rossetti, F. (2008). Subduction polarity reversal at the junction between the Western Alps and the Northern Apennines, Italy. *Tectonophysics*, *450*(1-4), 34–50. doi:10.1016/j.tecto.2007.12.012