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PLIO-PLEISTOCENE TECTONIC EVOLUTION OF SOUTHERN SARDINIA

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Presentata da: Dott. Fabrizio Cocco

Coordinatore Dottorato: Prof. Marcello Franceschelli

Tutor: Dott. Antonio Funedda

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ABSTRACT

Up to now there are not detailed studies about the structures and the kinematic related to the Plio-Pleistocene tectonics in southern Sardinia, although tectonic activity during the latest million years is long since known in the Island. Then, the general aim of this research is to improve the understanding of the recent geological evolution of the southern Sardinian block, trying to calculate the extension affecting the crust, to reconstruct the paleostress fields and to define a model of the tectonic evolution of the southern Sardinia during this period, considering the new data obtained from this research and the data available from literature on the geodynamic evolution of the western Mediterranean, in particular about the opening of the Tyrrhenian Sea. To achieve this purposes, the research focuses on the study of the most important structure related to the Plio-Pleistocene tectonics: the "so-called" Campidano graben. This structure has been studied mainly interpreting the seismic lines acquired in the Campidano plain by SAIS in the early sixties and by the joint venture AGIP-Progemisa S.p.A. in the early nineties that have been made available for this research by the Regione Autonoma della Sardegna and Progemisa S.p.A. The continuation of the Campidano in the Cagliari Gulf has been studied interpreting the ministerial seismic lines aquired by AGIP in the seventies in the offshore of Cagliari.

The main results achieved from the research are:

- the 3D model of the Middle Pliocene erosional surface at the base of the Samassi formation detected in the subsurface of the Campidano plain;
- the extension values and the deformation rates affecting the Campidano area during Plio-Quaternary times;
- the reconstruction of the paleostress field active during Pliocene time in the Campidano graben;
- a comparison between the structural setting of the Campidano and the structural setting of the southeastern Sardinian margin;
- the integration of the data achieved during this research with the data available from literature on the geodynamic evolution of the western Mediterranean, in particular about the opening of the Tyrrhenian Sea.

The 3D model of the Middle Pliocene erosional surface has been built using the two-way time structural maps of this surface carried out in both the northern and southern Campidano. This

surface shows a gently rolling landscape, typical of the erosion and planation surface developed in continental environments, both in the subsurface of the southern and northern Campidano plain. In the Campidano of Oristano, the maximum depth of the bottom of the Samassi formation is approximately -1100 m, while in the southern it is roughly -900 m (mean velocity assigned 2 km/s).

The two-way time structural maps show that both the northern and the southern Campidano graben are bounded in the western edges by master faults dipping to the east, but differences arise in the trends of the faults: mostly N-S in the northern Campidano and NW-SE in the southern Campidano.

N-S normal faults affected the whole Samassi formation and the within-plate basalts that post-date it, so we may admit that an important extension occurred after its deposition, that is in Pleistocene time.

The structures from seismic interpretation, that characterized the Plio-Quaternary evolution of the so-called Campidano graben have been validated during the drafting of the two-way time maps and with the structural and stratigraphic data available on surface. This allowed to construct a validated 3D model from which achieved the most possible reliable values of extension and paleostress.

To quantify the Plio-Quaternary deformation in southern Sardinia the 3D model of the Middle-Pliocene erosional surface (roughly 3.5 Ma in age) has been considered. The extension has been calculated restoring the cross-sections achieved from the 3D model. In the southern Campidano, extension values range from 205 m to 596 m and the percentage of extension from 1.65% to 5.72%. In the northern Campidano extension values range from 171 m to 465 m and percentage of extension from 0.84% to 2.50%.

Although the Plio-Pleistocene time-markers (3.5 Ma the erosional surface at the base of the Samassi formation and 2.5 Ma the surface sealed by the basalt lava flows in northern Campidano and a reflector calibrated with the Campidano1 well in the southern Campidano) are not very well constrained, they allow to estimate the vertical slip rate (0,6 mm/yr) and the extension rate (0,3 mm/yr in the northern Campidano and 0,4 mm/yr in the southern Campidano).

Considering the erosional surface sealed by the basalt-lava flows of the "giare" to the east of Campidano that occurs up to 550 m above the sea level and the age of 3.0 Ma of the basalts that seal it, an uplift rate of 0.18 mm/yr can be calculated if a marine origin for this surface is confirmed. Furthermore, the difference in elevation between the higher basalts that crop out in the central Sardinia (approximately 700 m in the Orroli basalt plateau) and those detected in the subsurface (-440 m in the northern Campidano) is related to tectonic activity that is at least Pleistocene in age. Therefore, during the whole Plio-Quaternary tectonics, considering the Middle Pliocene erosional surface at the base of the Samassi formation detected at -1100 m in the northern Campidano, vertical displacements on the order of 1800 m can be inferred.

The paleostress field active during Pliocene time in the Campidano area has been reconstructed using the movement vector on the fault plane achieved from the restoration of the Middle Pliocene erosional surface in both the northern and southern Campidano using two different methods that showed almost the same results.

In the northern Campidano, an extension oriented roughly E-W, with the principal stress axes: σ_1=263/77; σ_2=356/1; σ_3=86/13; has be inferred. In the southern Campidano, the extension is oriented roughly ENE-WSW, with the principal stress axes: σ_1=105/85; σ_2=332/3; σ_3=242/3.

The evolution during Pliocene in the southern Sardinia seems to be strictly related with the evolution of the sector of the southern Tyrrhenian basin located roughly south of the 40° parallel. This can be infer from the similarities in ages and stuctures in the eastern Sardinian margin and Campidano area. It seems that the extensional tectonics started in the Upper Miocene in the Sardinian Basin and Cornaglia Terrace and migrated westward in Sardinia and eastward in the Vavilov Basin.

Concerning the Pliocene tectonics affecting Sardinia, therefore, it seems to be directly related to the beginning of the extension in the Tyrrhenian Basin, due to the eastward roll back of the subducting Adriatic plate.

It seems, instead, that the Pleistocene tectonics recognized in Sardinia can not be related directly with the evolution in the Tyrrhenian Basin, because, although extensional tectonics continued in the Marsili Basin until now, no active tectonics occurs in the Sardinian Basin and Cornaglia Terrace. Thus, the recent uplift affecting the southern Sardinia is most likely related to the lithospheric structure inherited from the pre-Pliocene geodynamic evolution of the western Mediterranean, during which the lowering of the density in the mantle lithosphere could be caused an uplift up to 1620 m, if a normal thick mantle lithosphere (90 km) is considering as start point, or up to 720 m, considering the present day thinned mantle lithosphere (40 km), or by the thinning of the mantle lithosphere connected with process of intensive convective heating (thermal thinning).

1 INTRODUCTION

1.1 AIM OF THE RESEARCH

The island of Sardinia is usually considered a crustal block essentially stable in the latest million years of its geological history, although tectonic activity in Sardinia during Plio-Pleistocene time is long since known.

There are several evidences of this tectonic activity, to which a important volcanic activity is related, constituted mostly by wide plateau of lava flows of alkali-transitional basalts, emplaced from ca. 6 million years ago to the Lower Pleistocene (ASSORGIA *et alii*, 1983), cropping out in various areas of the Island. Often the volcanic products, and the surface they seal, are displaced showing tectonic activity that post-dates the occurrence of the basalts. Furthermore, several basaltic lava flows are nowadays clearly inverted reliefs, the so-called Giare, despite others flows are still in the present-day valley floor. These volcanic products crop out aligned along recent structures, like, for instance, the edges of the Campidano trough, or along older structure, like in the Orosei Gulf, probably reactivated during recent times.

Other evidences of recent tectonic instability are the occurrence of remarkable thickness of sediments in the Campidano trough (PECORINI & POMESANO CHERCHI, 1969; TILIA ZUCCARI, 1969; POMESANO CHERCHI, 1971; CHERCHI & MURRU, 1985) and in the Gulf of Palmas (CRISTINI *et alii*, 1982), related to the recent rejuvenation of reliefs, as clear in the southeast Sardinia, where the Flumendosa river deepens of 400 meters from the basaltic plateau of Orroli.

Up to now there are not detailed studies about the structures and the kinematic related to this Plio-Pleistocene tectonic activity in Sardinia, so the general aim of the research is to improve the understanding of the geological history of Sardinia during the last 5 millions years, trying to reconstruct the paleostress fields and define a model of the tectonic evolution of the island during this period, considering the new data obtained from this research and the data available from literature on the geodynamic evolution of the western Mediterranean, in particular about the opening of the Tyrrhenian Sea.

To achieve this general purpose, we decided to study the Campidano trough. First, because it is the most important and largest structure in Sardinia related to the evolution during Plio-Pleistocene time, second, because seismic lines acquired in the Campidano plain by SAIS in the early sixties and by the joint venture AGIP-Progemisa S.p.A. in the early nineties have been made available for this research by the Regione Autonoma della Sardegna and Progemisa S.p.A. In fact, the interpretation of these seismic lines allowed the production of geological sections perpendicularly to the most important structures of the Campidano trough, that also consider new detailed geological maps from the CARG Project, as well as other available geophysical data, especially gravimetric ones. The validation of these geological sections through restoration and balancing techniques allowed to build a three-dimensional model that is an additional validation of the geological interpretation but also allowed to evaluate the extension occurred during Plio-Pleistocene time. Once the extension and the paleostress field during the Plio-Pleistocene time was evaluated, these data have been integrated with those derived from the models on the opening of the Tyrrhenian Sea.

Then, schematically, the goals of the research are:

- to build a geological model geometrically correct of the Campidano trough, using balanced geological cross sections and three-dimensional models;
- to reconstruct the paleostress field during the Plio-Pleistocene time;
- to define a model of geodynamic evolution of Sardinia during Plio-Pleistocene time.

Furthermore, the results of this research, with a more detailed definitions of the geometries of the structures in the Campidano subsurface, can also contribute to the development and utilization of the renewable energy, like geothermal one, which is a key purpose of the Regione Autonoma della Sardegna regarding the energy resources.

1.2 GEOLOGICAL SETTING

In this paragraph we describe synthetically, from bibliographic data, the general geological setting of Sardinia and the different tectonic events that affected the island (Fig.1.1).

Usually, the Sardinia is divided into 3 main geological units, more or less equivalent in size:

- Paleozoic metamorphic basement (?Precambrian-Lower Carboniferous)
- Variscan batholith (Upper Carboniferous-Permian)
- Post-Variscan covers (Upper Carboniferous-Quaternary)

1.2.1 Paleozoic metamorphic basement

The Paleozoic metamorphic basement in Sardinia is part of the south European Variscan Belt, originated during the Carboniferous time. Originally, the basement of Sardinia was in continuity with those of the French Massif Central, the Montagne Noire and the Maures (ARTHAUD & MATTE, 1977; RICCI & SABATINI, 1978), before of the counterclockwise rotation of the Corsica-Sardinia block during Miocene time.

The majority of the authors agree that the Variscan orogeny evolved through subduction of oceanic crust and development of high pressure metamorphism from Silurian and continental collision during Devonian and Early Carboniferous (MATTE, 1986a; 1986b; CARMIGNANI *et alii*, 1994, Rossi *et alii*, 2009).

The geometry of the Variscan belt in Sardinia is even now recognizable. Metamorphism and deformation decrease from north to south, thus it has been possible differentiate the basement into three zones (CARMIGNANI *et alii*, 1994; 2001):

- the Axial Zone of the belt is in the North-East of the island, where, along the Posada-Asinara line, relics of oceanic crust crop out (CAPPELLI *et alii*, 1992). This area is also characterized by high-grade metamorphic rocks and migmatites;
- the Nappe Zone, characterized by the emplacement of several tectonic units, is divided into two zones: the Internal Nappe Zone, in the central-northern Sardinia, where mostly medium-grade metamorphic rocks crop out, and the External Nappe Zone, in the central-southern Sardinia, where only low-grade metamorphic rocks crop out. The differences between the Internal and External Nappe Zones are not only about the metamorphic grade, but also in the stratigraphic succession;

- the External Zone, in the South-West of Sardinia, is characterized by very low-grade metamorphic rocks.

1.2.2 Variscan batholith

Togheter with those of the Corsica, the Sardinian granites make up the Sardinian-Corsica Batholith. This is one of the most important in the European Variscan belt. The absolute datings with K-Ar and Rb-Sr give ages, for the emplacement of the granites, included around between 310 and 280 million years (DEL MORO *et alii*, 1975; 1991; DI SIMPLICIO *et alii*, 1975; FERRARA *et alii*, 1978; BECCALUVA *et alii*, 1985; SECCHI *et alii*, 1991; BROTZU *et alii*, 1994). The emplacement of the batolith between the Upper Carboniferous and the Lower Permian is contemporary to the post-collisional extensional tectonic of the Variscan belt (CARMIGNANI *et alii*, 1992; 1994). These granites are calc-alkaline in composition, and are prevalent in the Axial Zone.

During the late Carboniferous and Permian, in the Sardinia-Corsica block and in several areas of Variscan orogen, the volcanic activity also occurred.

Furthermore, the whole basement and part of the Permo-Carboniferous covers have been intruded by veins of several compositions and ages.

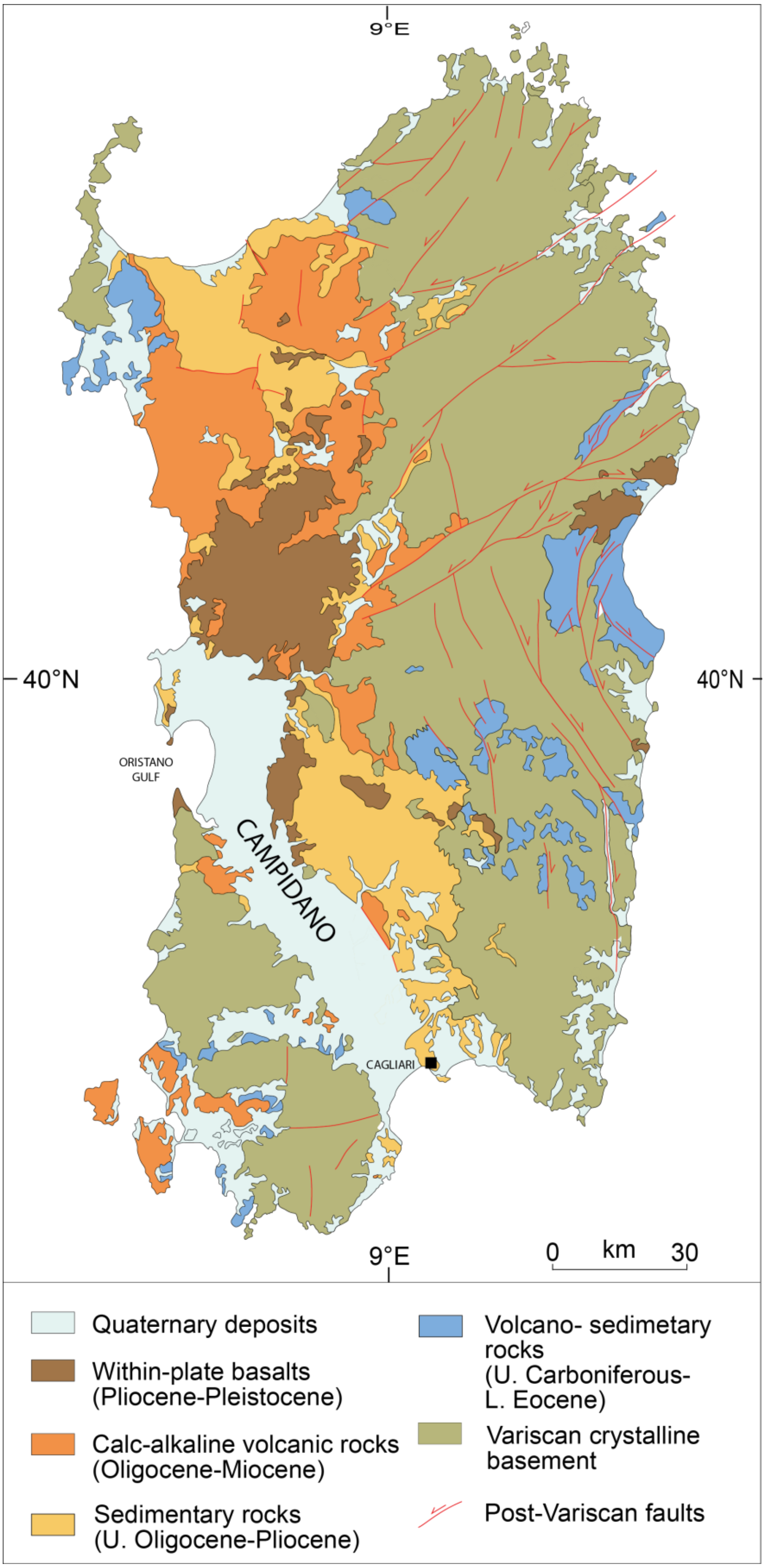


Fig.1.1- Geological sketch map of the main geological units and post-variscan features in Sardinia (modified from OGGIANO *et alii*, 2009)

1.2.3 Post-Variscan covers

The post-Variscan evolution of Sardinia has always been interpreted as a stable block, in conjunction with Corsica, exposed to periodic transgression and regression without important tectonic implications, although it was between two orogenic belts, the Pyrenees and the Appennines, until that the Sardinia-Corsica block has been delimited, before to the west and after to the east, respectively by the opening of the Balearic Basin in Miocene time and that of the central-south Tyrrhenian Basin in the Upper-Miocene-Pliocene.

During the Mesozoic, therefore, in Sardinia, no important tectonic or magmatic activity occurred. Although the transgressions in the Middle Triassic and the Lias, during the Triassic and Lower Jurassic the Sardinia would have to be a structural high. It had been transgressed from the Dogger, with dolomites and limestones that lie unconformable above the Paleozoic basement, the continental deposits of Late Paleozoic and the Permo-Triassic succession. Furthermore, in both the Mesozoic succession of Nurra and Sulcis, during the Middle-Cretaceous, a hiatus occurred associated with angular unconformity and bauxite deposits. From the Late Cretaceous to almost the whole Paleocene in Sardinia persisted continental conditions.

A new transgression occurred in the Lower Eocene, characterized by terrigenous to carbonate succession with predominant macroforaminifera (PECORINI & POMESANO CHERCHI, 1969; MURRU & SALVADORI, 1990; BARCA & COSTAMAGNA, 2000; CARMIGNANI *et alii*, 2001*a*; 2001*b*; PERTUSATI *et alii*, 2002*a*; 2002*b*). Related to the Pyrenean tectonic evolution (BARCA & COSTAMAGNA, 1997; 2000; CARMIGNANI *et alii*, 2004), in Middle-Upper Eocene new continental stage occurred, persisting for the whole Oligocene almost, as the fluvial and lacustrine deposits of Cixerri Formation (PECORINI & POMESANO CHERCHI, 1969), referred to this age, demonstrate.

The structural setting during the Upper-Oligocene and Lower-Miocene is characterized, in north of Sardinia, by strike-slip faults (PASCI, 1997; OGGIANO *et alii*, 2009), to which are related both transpression and transtension zones, where pull-apart basins are filled by continental deposits Upper Oligocene-Aquitanian in age, coeval with an important volcanic activity. There are two different explanation for the geodynamic evolution of Sardinia during later Oligocene and Early Miocene at least: the first considers an extensional tectonic evolution from Upper-Oligocene, with the development of a tectonic trough that now crossed the Sardinia from the Cagliari Gulf to the Asinara Gulf (CHERCHI & MONTADERT, 1982;

1984; CASULA *et alii*, 2001); the second one suppose that during the Upper Oligocene-Lower Aquitanian the Sardinia was the hinterland of the collision between South European Margin and Adria Margin that originated the northern Appennines (CARMIGNANI *et alii*, 1994; CARMIGNANI *et alii*, 1995; OGGIANO *et alii*, 2009). The Aquitanian basin are for this reason related to the Apennine collisional evolution, whereas the following Burdigalian basins would have been consequence of the counterclockwise rotation of the Sardinian-Corsica block and related opening of the Balearic basin. Related to the these ones occurred also an important calkalcaline volcanic activity, characterized by great widespread and remarkable thickness (LECCA *et alii*, 1997).

In the Pliocene the Sardinia was affected by another extensional event, most likely related to the opening of the southern Tyrrhenian basin. The most important structure related to this geodynamic event is the so-called Campidano Graben, located between the Cagliari Gulf and the Oristano Gulf. This further extensional phase is characterized also by the occurrence of within-plate alkaline basalts that crop out in several areas of the island.

This last part will be discussed more in detail in the next paragraphs.

1.3 EVIDENCES OF PLIO-PLEISTOCENE TECTONICS IN SARDINIA

1.3.1 General geography of Sardinia

Sardinia is the second largest island of the Mediterranean Sea, with an area of 24.090 km^2. It is located between 38°51' and 41°15' of latitude north and 8°8' and 9°50' of longitude east, in the center of the western side of Mediterranean Sea, between the Sea of Sardinia on the west and the Tyrrhenian Sea on the east. To the south there is the Sardinian Channel and to the north the Bonifacio Strait separates it from the Corsica island.

The territory of Sardinia is characterized by 67,9% of hills, 18,5% of plains and 13,6% of mountains.

The highest peaks are part of the Gennargentu Range, in the center of the island, with Punta la Marmora (1834m), Bruncu Spina (1829m) and Monte Spada (1595). In the north the Monte Limbara reaches 1359m. In the eastern part, in the calcareous areas called Supramontes, Monte Corrasi reaches 1463m. In the Sulcis-Iglesiente area, in the southwestern part of the island, the most important peak is Monte Linas (1236m).

The vastest plains are the Campidano, located in the southwest between the Gulf of Cagliari and the Gulf of Oristano, and the plain of Nurra in the northwest.

Typical landscapes in Sardinia are the so-called Giare, small, flat plateaux modeled because of the inversion of topography of basaltic lava flows. The most important are the Giara of Gesturi and Giara of Orroli in thecentral part of the Island.

The coasts are characterized for the presence of four important gulfs: Asinara Gulf in the north, Oristano Gulf in the west, Orosei Gulf in the east and Cagliari Gulf in the south. For a total of 1897 km the costs are high with little creeks (cale) that are deeper in the north-east (rias). Low-rise and sandy coasts are typical mostly in both the Cagliari and Oristano Gulfs, areas also characterized by the presence of backshore ponds.

Sardinia is surrounded by several little islands: the biggest are Sant'Antioco and San Pietro in the south-west, Asinara in the north-west and La Maddalena and Caprera in the north-east.

The major rivers are the Tirso (159 km), the Flumendosa (127 km) and the Coghinas (115 km), which flow respectively into the Gulf of Oristano, the Tyrrenian Sea and the Asinara Gulf.

The actual geographic features of Sardinia are strictly related to the recent geological evolution of the island, especially to the uplift processes likely affected the Sardinian crust in the latest million years.

1.3.2 Evidences of Plio-Pleistocene tectonics

Tectonic activity in Sardinia during Plio-Pleistocene time is a long time known. Sets of problematic extensional structures, as the Campidano graben, and others less clear, as the extensional faults systems in northern and eastern Sardinia, can be recognised. Frequently, volcanic activity is related to these recent (sometimes reactivated) structures. Plio-Quaternary volcanism in Sardinia consist of a wide variety of rocks that crops out in several areas of the Island, ranging from mafic to silicic and from subalkaline (roughly 20% of erupted magmas) to alkaline (roughly 80%). The majority of erupted magmas are mafic rocks and range from composition that are oversaturated to strongly undersaturated in silica (PECCERILLO, 2005). Several datings of these rocks are available (LUSTRINO *et alii*, 2007, and reference therein). The oldest volcanic products (6.6-6.4 Ma) crop out in the southeastern Sardinia (Capo Ferrato) and are characterized by lava flows, domes and dykes with trachyandesitic and trachytic composition. In southern Sardinia the necks of Guspini (4.4 Ma) and Rio Girone occur, with hawaiitic and basanitic composition, respectively (PECCERILLO, 2005). The Monte Arci (3.8-2.6 Ma) is a 20 km long N-S trending volcanic ridge, located in the eastern edge of the northern Campidano plain, formed of dacite and rhyolite lavas with minor basalts, trachybasalts and andesites (ASSORGIA *et alii*, 1976; MONTANINI *et alii*, 1994).

The Montiferro volcanic complex (3.9-1.6 Ma), wide 400 km^2, is characterized by basanites, hawaiites, mugearites, trachytes and phonolites forming mainly lava flows, domes and dykes (BECCALUVA *et alii*, 1977; ASSORGIA *et alii*, 1981; LUSTRINO *et alii*, 2004). The Montiferro volcanic complex is located to the north of the northern Campidano plain, where the intersection between one of the main northern Sardinia fault (Nuoro fault) and the Campidano graben occurs. To the east of the Montiferro there is the Campeda-Paulilatino-Abbasanta-Planargia basaltic plateau (3.7-3.5 Ma), characterized by tholeiitic (basaltic andesite) to Na-alkaline mafic to intermediate lava flows (hawaiites, mugearites) covering an area of about 850 km^2 (BECCALUVA *et alii*, 1997; LUSTRINO *et alii*, 2004). This basaltic plateau is divided into two blocks with the mean sea level altitude of 350 m and 650 m to the south and to the north respectively. The Orosei-Dorgali volcanic area (2.1 Ma, unplublished data from CARG project), in the eastern Sardinia, is made up of subaerial and submarine lavas composed predominantly of hawaiites and mugearites and minor tholeiitic basaltic andesites (BECCALUVA *et alii*, 1976; LUSTRINO *et alii*, 2002). Apart this wide plateaux, in central Sardinia crop out also small centres. To the west the peninsulas of Capo Frasca and Sinis (no radiometric ages are available) are characterized by small outcrops of basaltic andesite lavas, like the San Pietro of Baunei outcrop to the east, that can be related to the volcanic activity in the Orosei-Dorgali area (LUSTRINO *et alii*, 2000). Near Barisardo (Teccu), again in the central-eastern part of the Island, crops out a small volcano composed of hawaiite, mugearite and few basaltic andesite lava flows (PECCERILLO, 2005). In the central Sardinia volcanic area (3.5-2.1 Ma), the landscape is characterized by the so-called Giare (Gesturi, Nurri, Siddi, Serri, Orroli), formed by several small scattered centres of basaltic andesite, hawaiite and mugearite lavas that overlie Hercynian basement and Mesozoic sediments (LUSTRINO *et alii*, 1996; 2000). In the northern Sardinia (Logudoro) occurs the youngest volcanic activity. Indeed, a Middle Pleistocene (0.9-0.1 Ma) volcanic rocks crop out, as well as older ones (2.4 Ma). Here, the eruptive centres consist of several monogenetic spatter cones, cinder cones and lava flows, associated with minor pyroclastic deposits erupted along N-S and NE-SW faults, and covering an area of about 500 km^2. The volcanic rocks lie on Miocene sediments and Oligo-Miocene calc-alkaline volcanic rocks. Composition are mafic and mainly alkaline with sodic and mildly potassic affinity; subalkline rocks occur in minor amounts. Rock types includes basanites, trachybasalts, basaltic trachyandesitic and basaltic andesites (BECCALUVA*et alii*, 1976; 1977; 1985; SAVELLI, 1988; GASPERINI *et alii*, 2000).

The Plio-Pleistocene volcanic activity in Sardinia represents an important geodynamic marker, exhibiting intraplate signatures (BECCALUVA *et alii*, 1985; LUSTRINO *et alii*, 2004). Furthermore, the datings of these rocks allow to constrain, sometimes, the age of the deformation. There are therefore evidences of Plio-Pleistocene tectonics for example in the Logudoro area (FUNEDDA *et alii*, 2000). Here, the basaltic lava flow of Monte Santo and Monte Pelao, that seals the same surface made up by limestones of the Calcari di M.Santo formation, ?Tortonian-Lower Messinian in age (MAZZEI & OGGIANO, 1990), is displaced (Fig.1.2). Furthermore, in this area, some basaltic lava flows are, today, in the current valley floor, while others are clearly inverted reliefs, like Monte Santo and Monte Pelao cited above. Other important inverted reliefs occur also in the central Sardinia, constitued by the "Giare" mentioned before, showing a recent rejuvenation of reliefs. This is especially clear to the east of the Campidano plain, where the Flumendosa river carves the Sarcidano-Gerrei horst of at least 400 m from the Orroli basaltic plateau in the last 2,5 Ma. This strong erosion activity of the Flumendosa river is probably also due to a recent tectonic and uplift, as well as to glacio-eustatic sea level fluctuation. Patta (2003) reported in the eastern side of Campidano the occurrence of a displaced fluvial terrace of Upper Pleistocene age.

Apart from the evidences of the surface geology, the Plio-Pleistocene tectonic activity is shown also from the thickness of the Plio-Quaternary deposits discovered in the subsurface. A survey in the isthmus of Sant'Antioco Island showed 260 m of Plio-Pleistocene continental deposits, mainly fluvial with subordinate lacustrine. Furthermore, Thyrrenian deposits are found out at -19 m and -14 m showing an active subsidence after 0.1 Ma and that can be considered presently active because of an ancient Roman road nowadays submerged (CRISTINI *et alii*, 1982). Also the wells drilled in the Campidano plain by SAIS (Società per Azioni Idrocarburi in Sardegna) show important thickness of Plio-Quaternary deposits. In the northern Campidano the Oristano 1 and Oristano 2 wells found out at -820 m and -729 m, respectively, the bottom of Pliocene deposits (TILIA ZUCCARI, 1969; POMESANO CHERCHI, 1971). In the Campidano 1 well in the southern Campdano the bottom of Pliocene deposits are found at -540 m (PECORINI & POMESANO CHERCHI, 1969) and in the Marcella well, drilled by AGIP in the offshore of Pula (southwestern of Cagliari Gulf), at

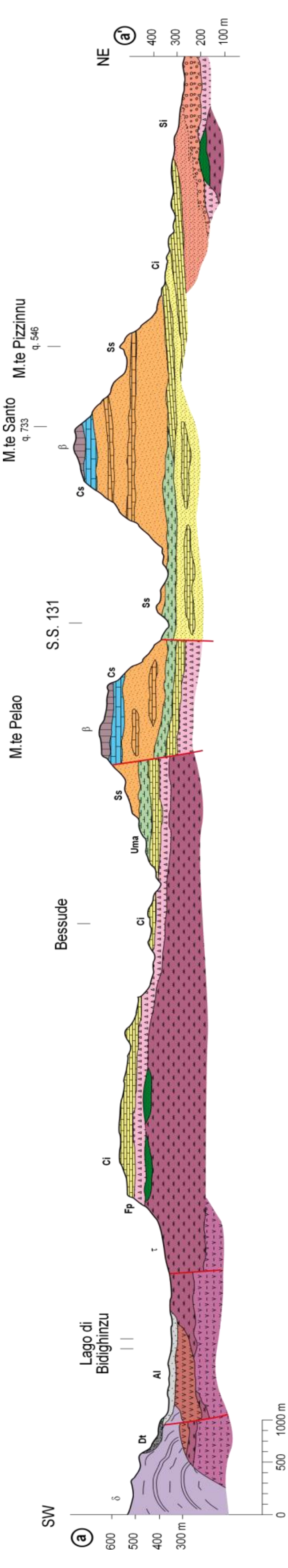


Fig.1.2- Geological cross-section in the Miocenic Logudoro basin (FUNEDDA *et alii*, 2000). β: Plio-Quaternary basalts; Cs: "Upper Limestones" (?Tortonian-Lower Messinian); Ss: "Upper Sandstones" (Serravalian); Uma: marl-arenaceous Unit (Langhian); Ci: "Lower Limestones" (Upper Burdigalian); Si: "Lower Sandstones" (?Upper Burdigalian); Green: lacustrine sediments (?Burdigalian); Fp: Pyroclastic flow (?Burdigalian); τ: rhyolitic ignimbrite (Oligo-Miocene); α: Andesite lava flows and domes (Oligo-Miocene).

-350 m (CHERCHI & MURRU, 1985). This data, concerning the Campidano, will be explain in detail in the next paragraph.

Other evidences of recent tectonics occur in the limestone cliffs both in the Orosei Gulf, in the central eastern Sardinia, and Capo Caccia peninsula, in the northwestern. The cliffs display notchs of Marine isotope Sub-Stage (MIS) 5.5 (0.12 Ma) that are tilted (CAROBENE, 1972; FERRANTI *et alii*, 2006).

In the coastal sector between Funtanamare and Capo Giordano (southwestern Sardinia) deposits composed mainly by different dune generation, and subordinate fluvial and colluvial deposits assigned to Early to Middle Pleistocene (ORRÙ & ULZEGA, 1986) are displaced by two fault systems, striking NNE-SSW and ESE-WNW (BUTTAU *et alii*, 2011).

1.4 THE CAMPIDANO GRABEN

The Campidano graben is a tectonic trough that coincides roughly with the plain of the same name, that trends NNW-SSE for more than 100 km from Oristano Gulf to Cagliari Gulf and it is wide on average 20 km. The Campidano plain is the largest flat area in Sardinia.

The altitude in the Campidano plain reaches at most 50 m, whereas in the western mountains of the Sulcis-Iglesiente-Arburese block heights exceed 1000 m. The eastern block (Marmilla-Trexenta) is characterized by hills that reach on average 400 m in height. Close to the Guspini-Sardara alignment a watershed occurs that separates the hydrographic basins of Cagliari, where the most important river is the Flumini Mannu, and Oristano with Flumini Malu and Flumini Belu.

As already mentioned above, the Campidano graben is the most important structure related to the geodynamic evolution of Sardinia in Plio-Pleistocene time. Thus, in this paragraph we present the previous works that concern the stratigraphic and structural setting of the areas sourrounding the Campidano and the geological setting of the trough.

1.4.1 Previous works

Already in the nineteenth century the Campidano area has been the subject of geological researches and recognised as a tectonic trough (LAMARMORA, 1857). Other works concern mainly paleontology and the stratigraphy of the hills of Cagliari (LOVISATO, 1885; 1901; 1902; PARONA, 1887; 1892; FORNASINI, 1887; BASSANI, 1891) and Sinis peninsula (MARIANI & PARONA, 1887). Following, studies on the geomorfology and stratigraphy of the Campidano plain with hints on the tectonic setting of the trough have been made (FERUGLIO, 1924; GORTANI, 1935; GORTANI & LIPPARINI, 1935; VARDABASSO, 1934; 1955; 1962; MAXIA, 1936; MONTALDO, 1950; 1958; 1959a; 1959b; 1967; MORETTI, 1953; POMESANO CHERCHI, 1967; MAXIA *et alii*, 1970). All this Autors agree in retain recent in age the Campidano trough, whereas CAVINATO (1939) retains the Campidano a large syncline modeled before the deposition of permian succession.

The geological cartography in scale 1:100,000 (Servizio Geologico d'Italia), realized with the field surveys during the first half of the twentieth century, allowed to have a global vision of the stratigraphy and structures characterizing the Campidano and surrounding areas (Fogli 233 Carbonia, 1938; 234 Cagliari, 1943; 226 Mandas, 1959; 224-225 Capo Pecora-Guspini, 1971; 205-206 CapoMannu-Macomer, 1988; 216-217 Capo San Marco-Oristano, 1989). Other detailed geological maps and field survey have been realized for several purposes as hydrogeological researches (PALA *et alii*, 1976; 1982; PALA & VACCA, 1980; PALA & COSSU, 1994) or stratigraphic and paleontological researches (CHERCHI, 1973; CHERCHI *et alii*, 1978; MARINI *et alii*, 1979; MARINI & MURRU, 1981; BARCA *et alii*, 2000; PATTA, 2003; ANDRÉ *et alii*, 2004; CORNÉE *et alii*, 2008). Some more recent geological maps in scale 1:50,000 are now available (Carta Geologica d'Italia, Fogli 528-Oristano, 540-Mandas, 547-Villacidro, 548-Senorbì, 556-Assemini, 557-Cagliari, 565-Capoterra, 566-Pula).

Regarding the subsurface stratigraphy of the Campidano graben, the more reliable data come from some wells drilled for hydrocarbon researches, that reach almost 2000 m in depth, and those for hydrogeological research, deep sufficiently to pass at least the Quaternary deposits. Of these wells, detailed stratigrafic studies have been published (PECORINI & POMESANO CHERCHI, 1969; TILIA ZUCCARI, 1969; POMESANO CHERCHI, 1971; MURRU, 1983a; 1983b; CHERCHI & MURRU, 1985; FRAU, 1994).

The structural setting of the Campidano graben has been studied also with geophysical methods for hydrocarbon and geothermal researches, and several models are available (SALVADORI, 1959; TRUDU, 1953; 1961a; 1961b; 1963; FANUCCI *et alii*, 1976; FINZI-CONTINI, 1982; MARCHISIO *et alii*, 1982; BALIA *et alii*, 1984a; 1984b; 1988; 1990; 1991a; 1991b; 1991c; CIMINALE *et alii*, 1985; CASULA *et alii*, 2001). Nevertheless, the only works aimed at understand the tectonic activity during Plio-Quaternary times in the Campidano area are those carried out for the "Geodynamic Project, Sub-project Neotectonics" of the C.N.R. (Consiglio Nazionale delle Ricerche), that had the goal of the achievement of the Neotectonic Map of Italy (CHERCHI *et alii*, 1978a; 1978b; 1979; MARINI & MURRU, 1983).

1.4.2 Stratigraphy

1.4.2.1 Paleozoic Metamorphic Basement

The Paleozoic Metamorphic Basement that crops out in the sourrounding areas of the Campidano graben is part of the External Nappe Zone and External Zone of the Sardinian segment of the Variscan belt.

The basement crops out almost along the entire western edge of the Campidano graben. The southwesternmost edge is part of the External Fold and Thrust Zone, whereas the basement that crops out from Capoterra to the Marceddì pond and Capo Frasca peninsula, is part of the Arburese Unit of the External Nappe Zone.

The eastern edge is characterized by few outcrops of basement, all pertaining to the External Nappe Zone: the Sarrabus Unit crops out just to the east of Monastir and close to Nuraminis, whereas can be referred to Gerrei Unit the outcrop near Sardara, where is the Monreale castle. To the north of Monte Arci, the Monte Grighini Unit occurs.

Generally, the basement is composed by volcanic and siliciclastic rocks characterized by very low grade metamorphism where the petrographic and sedimentological features of the protolytes is almost always preserved. The metamorphic grade is higher in the Monte Grighini Unit where reaches the amphibolite facies (CARMIGNANI *et alii*, 2001 and references therein).

1.4.2.2 Variscan batholith

The Variscan batholith crops out mainly in the western edge of the Campidano graben. In the southwesternmost part, near Capoterra, it is constitued by monzogranites, leucogranites and granodiorites. The other outcrops are close to Villacidro where prevalently leucogranites crops out and close to Guspini where the batholith are characterized by paralluminous granites. In the eastern side, the outcrops are not just on the edge, but occur more distant, as the monzogranites of Barrali and Pimentel. To the north we can point out the sin-kinematic granites of the Monte Grighini and the monzogranites of the Mal di Ventre Island in the offshore of the Sinis peninsula (CARMIGNANI *et alii*, 2008; Geological Map of Sardinia).

1.4.2.3 Triassic succession

The Mesozoic succession, that crops out rather extensively in Sardinia, in the sourrounding areas of the Campidano is represented only by a small outcrop of Middle Triassic inside Guspini, characterized by the Muschelkalk Germanic facies and faunas (ANNINO *et alii*, 2000).

1.4.2.4 Cenozoic volcano-sedimentary succession

1.4.2.4.1 Paleogenic sedimentary succession

Up to now, in southern Sardinia, have been recognised with certainty of Paleogenic period the transitional and littoral deposits of the Monte Cardiga Formation (Lower Eocene) and those continental of Cixerri Formation (Middle Eocene-? Upper Oligocene).

1.4.2.4.1.1 Monte Cardiga Formation

In the surrounding areas of Campidano only a small outcrop of Monte Cardiga Formation occur, roughly 1 km to the east of Segariu, in the eastern edge of the graben. In this outcrop, two different sedimentary facies occur. The clastic facies is characterized by coarse sandstones and quartz conglomerates whereas the carbonatic facies is characterized by sandy limestones, darkish-grey in color, enriched in blackish ostrea faunas (*Pycnodonta*), that indicate infralittoral bathymetric facies. These sediments represent residual outcrops of the Eocene transgression displaced and isolated during the wide-spread Oligo-Miocene volcanic eruptions, underlying an apparent stratigraphic contact. The age of this outcrop is referred to Lower Eocene (BARCA *et alii*, 2011).

1.4.2.4.1.2 Cixerri Formation

The Cixerri Formation (PECORINI & POMESANO CHERCHI, 1969) constitutes the substratum of the Cixerri valley, cropping out therefore mainly in the western edge of the Campidano, although some outcrops in the eastern edge, close to Monastir and Nuraminis, have been referred to this formation. It is composed by clayey reddish siltstones and sandstones of continental environment. At the base locally ematitic conglomerates with clasts of the Variscan basement occur. The depositional environment can be ascribed to a wide alluvial plain system prograding toward east (BARCA & PALMERINI, 1973). The Cixerri Formation is interpreted as a post-Pyrenean molasse (CHERCHI, 1979; BARCA & COSTAMAGNA, 1997). The age of the Cixerri Formation can be referred to Middle Eocene-

Upper Oligocene, because, in the Iglesiente-Sulcis, both in outcrop and boreholes, lies above the Lower Eocene formations, is intruded by Upper Oligocene volcanics and is sealed by Aquitanian sediments.

1.4.2.4.2 Oligo-Miocene volcano-sedimentary succession

From the Upper Oligocene till Tortonian the occurrence of volcano-sedimentary successions involves the Island of Sardinia from Cagliari to Asinara gulfs, related to Alpine-Apennine geodynamic evolution that originates several sedimentary basins known as "Fossa Sarda" or "Rift Sardo". About the evolution of these basins different interpretations exist (CHERCHI & MONTADERT, 1982; ASSORGIA *et alii*, 1997; FUNEDDA *et alii*, 2000; CARMIGNANI *et alii*, 2001; CASULA *et alii*, 2001; OGGIANO *et alii*, 2009).

Besides the Oligo-Miocene volcanic succession, the majority of the Authors agree with the separation of the sedimentary succession into three cycles (Fig.3.1): the "I Miocenic cycle" Upper Oligocene-Lower Burdigalian in age, the "II Miocenic cycle" Upper Burdigalian-Langhian in age and the "III Miocenic cycle" Serravalian-Tortonian-?Messinian in age.

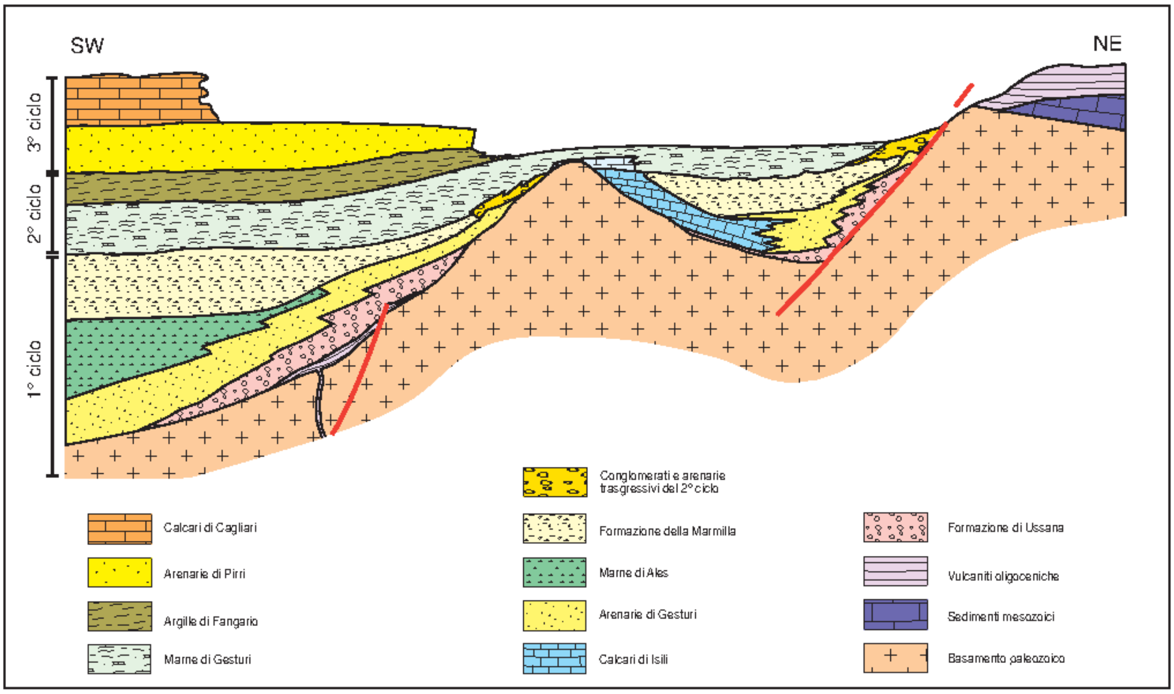


Fig.1.3- Stratigraphic relationships among the Miocene formations in southern Sardinia (CARMIGNANI *et alii*, 2001).

1.4.2.4.2.1 Oligo-Miocene volcanic succession

The Oligo-Miocene volcanism in Sardinia represents one of the most important Cenozoic geologic event in the western Mediterranean. The importance of this volcanic cycle is shown by the wide size of the outcrops and the remarkable thickness of the volcanic succession that reach several hundreds meter.

In the sourrounding areas of the Campidano plain, the main Oligo-Miocene volcanic districts are the complexes of Sarroch, Siliqua, Monastir and Serrenti-Furtei in the southern Campidano and, in the northern Campidano, the Arcuentu volcanic complex.

The Sarroch volcanic complex is in the western side of the Cagliari Gulf. It is characterized by andesitic lavas and pyroclastic flow with lithic fragments of Variscan batholith and basement. Andesite-dacyte veins also occur. The age is Chattian to Aquitanian (BARCA *et alii*, 2009, and references therein; CARTA GEOLOGICA D'ITALIA, FOGLIO 566 PULA).

In the Cixerri valley crop out the calcalkaline sub-volcanic and effusive rocks of the Siliqua volcanic complex. The most important outcrop is a 4 km^2 dome close to the western edge of the Campidano graben, known as "Soglia di Siliqua" (PECORINI & POMESANO CHERCHI, 1969; PALA *et alii*, 1976; 1982). Two reasons allow to consider these rocks different and not directly correlated with the other outcrops of the Oligo-Miocene volcanic cycle. First, they are mainly intrusive rocks, whereas the majority of the other outcrops are formed by effusive products; second, the ages are older than those of the other volcanic outcrops and can be referred to the Upper Oligocene (LECCA *et alii*, 1997).

In the eastern edge of the Campidano crops out the Monastir volcanic complex, that is characterized by lava flows and rare hypoabyssal lava bodies, with alternating rare pyroclastic deposits, of andesitic composition. These rocks are Chattian in age (BARCA *et alii*, 2005, and references therein).

The volcanic district of Serrenti-Furtei occupies the area included among the villages of Furtei, Segariu and Serrenti, in the eastern edge of the Campidano graben. In this sector the oldest volcanic phase is characterized by andesitic lavas and domes. Then volcanic explosive activity occurs with block and ash flow deposits. The correlation, founded on lithological and compositional criteria, with other volcanic rocks of the same cycle, seggests a Upper Oligocene age for this volcanic district (PECORINI, 1966), that has been confirmed by K/Ar datings (BECCALUVA *et alii*, 1985).

The Monte Arcuentu volcanic complex (Arburese) is characterized by a volcanic events succession basic to acid in composition, alternated with marine and continental sediments (ASSORGIA *et alii*, 1986a; 1986b; 1992; ASSORGIA & GIMENO, 1994) and separated into two different cycles. The basic products are mainly basaltic lava flows. The acid products are mainly rhyolites and rhyodacites. The radiometric datings (ASSORGIA *et alii*, 1984) and the stratigraphic location (ASSORGIA *et alii*, 1986a) suggest for these volcanic sequences an age between the Upper Oligocene and the Burdigalian. Veins of 18,3-16,7 Ma (ASSORGIA *et alii*, 1984) intrude the entire succession.

Younger volcanic rocks, but always part of the calc-alkaline Oligo-Miocene volcanic cycle, crop out just in the north of the Campidano. These outcrops can be divide into two sequences.

The first, Burdigalian in age, is characterized by lava flows and outoclastic breccias of andesitic composition and the second, Upper Burdigalian-Langhian in age, characterized by pyroclastic flow in one or more units, with rhyolitic and dacitic composition, with vitrofiric and brecciated layers.

1.4.2.4.2.2 1° Miocene Sedimentary Cycle

The 1° Miocenic Sedimentary Cycle occur only in the eastern edge of the Campidano graben. It is characterized by an evolution of the sedimentary basins that bagins with the clastic sediments that constituted the Ussana Formation, follow by the transitional and ciraclittoral marine sediments of the Nurallao Formation. The sedimentation, in part heteropic, in more distal deposits with lower energy transport is shown by the siltstones of the Marmilla Formation, with abundant volcanoclastic components. The carbonate facies, sedimented in environment of high waves energy, are typical limestones reef (Villagreca limestones). These are heteropic with all the other cited Formations.

The Ussana Formation (PECORINI & POMESANO CHERCHI, 1969) crops out discontinuously along the entire eastern edge of the Campidano, from the area close to the villages of Ussana, Monastir and Nuraminis in the south to the small outcrops near the Monte Grighini and the Sinis peninsula in the north. It is characterized by polygenic conglomerates with pebbles and blocks of several sizes, from centimetric to metric, with, sometimes, alternated layers of claystones and siltstones. In the upper part it is constituted by microconglomerates, sandstones and claystones sometimes fossiliferous. The depositional environments vary from continental slope and alluvial fan to alluvial plain with transition to fluvial-lacustrine, lagoon and littoral environments. CHERCHI & MONTADERT (1984) consider this formation, with the overlying Aquitanian marine sediments, as syn-tectonic deposits related to the evolution of "Rift Sardo", that should be the easternmost part of the European Cenozoic Rift System (CHERCHI & MONTADERT, 1982). SOWERBUTTS & UNDERHILL (1998) similarly consider these deposits coeval with the occurrence of normal faults. Because the Ussana Formation is coeval with other clastic deposits in northern Sardinia and Corsica, CARMIGNANI *et alii* (1992, 1994) consider this formation related to the north-Appennine collision that predates the Burdigalian extensional tectonics. The base of the Ussana formation is not older than Middle-Upper Oligocene, because of the occurrence, in the conglomerates, of pebbles of Oligocene volcanics, that, in addition to this, underlie the Ussana formation. The bottom can be probably attributed to the Lower Aquitanian (PECORINI & POMESANO CHERCHI, 1969).

The Nurallao Formation (FUNEDDA *et alii*, 2012) crops out in the southern part of the eastern edge of the Campidano. It marks the beginning of the marine sedimentation and is divided into two member according to depositional environment: Duidduru conglomerate and Serra Longa sandstones. The Duidduru member consists of conglomerates with carbonate matrix intercalated, sometimes, with lenses of sandstones and sporadic biocalcarenites. Locally, in this member, blocks of several meters in size occur. The Serra Longa member consists of sandstones with the occurrence locally of calcarenites and fossiliferous carbonate sandstones. The depositional environment of the Nurallao Formation varies from transitional to littoral-marine that follows those continental of the Ussana Formation. Upward and laterally the Villagreca limestones and Marmilla Formation occur. The stratigephic position and the fossils allow to attribute the Nurallao Formation to an age including between the Upper Oligocene to Lower Burdigalian (CHERCHI & MONTADERT, 1984).

The Villagreca limestones crop out in the eastern edge of the Campidano graben near the villages of Nuraminis, Villagreca and Samatzai. To the north outcrops of this formation occur close to Mogoro and, in the western side of the Campidano, in the Sinis peninsula. It is composed by hermatypic limestones and carbonate sandstones, with interlayered rare siliciclastic sediments, with molluscs. The age of the Villagreca limestones is referred to Aquitania-Lower Burdigalian (PECORINI & POMESANO CHERCHI, 1969; CHERCHI, 1974; 1985), but more recent datings (FUNEDDA *et alii*, 2012) gave ages between 24,47±0,27 and 21,40±0,16 (Upper Oligocene-Lower Burdigalian).

The Marmilla Formation crops out extensively and continuously in the eastern side of the Campidano from the village of Nuraminis to the Monte Grighini northward. It is characterized by alterned marls and sandstones, with high volcanic component, of distal marine environment. This formation is often affected by sin-sedimentary faults. Usually the Marmilla formation lies above the Serra Longa member of the Nurallao Formation, with which has also heteropic contact, as well as with the Villagreca limestones. It is sealed by the deposits of the 2° Miocenic sedimentary cycle. The contact between them is characterized by low angle unconformity and by the sporadic occurrence of conglomerates. The recognition of the *Globigerinita dissimilis* biostratigraphic zone (PECORINI & POMESANO CHERCHI, 1969; CHERCHI, 1974; 1985) allows to refer the Marmilla Formation to Aquitanian-Lower Burdigalian age.

1.4.2.4.2.3 2° Miocene Sedimentary Cycle

In the Upper Burdigalian begins the transgression of the 2° Miocenic Sedimentary Cycle, that lies unconformably above on both the 1° Miocenic Sedimentary Cycle and Paleozoic Basement. In the northern Sardinia, between two cycles thick volcanic sequences and continental deposits occur (MAXIA & PECORINI, 1969; SPANO & ASUNIS, 1984; OGGIANO *et alii*, 1987; MARTINI *et alii*, 1992), that are rare in the central and southern Sardinia. The volcanic activity ends in the Upper Burdigalian, but small pyroclastic layers in the hills to the east of Cagliari are attributed to the Langhian (PECORINI, 1974).

The Gesturi marls Formation crops out in the eastern-southern edge of the Campidano and northward lies below the Plio-Pleistocene basaltic lava flow of the Giara of Gesturi and Monte Arci. It is composed of alternated arenaceous and siltitic marls with intercalated sandstones. Locally, limestones with *Lithothamnium* occur (LEONE *et alii*, 1984; IACCARINO *et alii*, 1985). In the marl-arenaceous succession some layers of epiclastites are intercalated. One of this, thick from 4 m to 20 m, crops out continuously from the Marmilla to the Gulf of Cagliari, included into the *Globigerinoides bisphericus* and *Orbulina suturalis* biozones (Langhian) (PECORINI, 1974). The depositional environment is epibathial-bathial for the marl-arenaceous succession, while it is neritic for the carbonate sediments (CHERCHI, 1985; IACCARINO *et alii*, 1985). The biostratigraphic units (*Globigerinoides bisphericus* and *Preorbulina glomerosa* biozones) suggest an age between the Upper Burdigalian to Middle-Upper Langhian (PECORINI & POMESANO CHERCHI, 1969; CHERCHI, 1974;

1985; ROBBA & SPANO, 1978; LEONE *et alii*, 1984; IACCARINO *et alii*, 1985; ODIN *et alii*, 1994).

Above the Gesturi marls the Miocenic succession continues with the Fangario clays, composed by clays and marls with layers, upward, of marl-sandstones. This formation crops out only in a few and small areas to north-west of Cagliari. The stratigraphic contact with the overlying Pirri sandstones is erosional, but sometimes the Pirri sandstones lie directly above the Gesturi marls, suggesting that the Fangario clays can be partially heteropic with they. The depositional environment is epibathial to bathial. The age of this formation, considering the biozones, is attributable to Middle Langhian-Lower Serravalian (COMASCHI CARIA, 1958; CHERCHI, 1974; 1985; ROBBA & SPANO, 1978; BARBIERI & D'ONOFRIO, 1984; BARBIERI *et alii*, 1985; CORRADINI, 1985; IACCARINO *et alii*, 1985; SPANO, 1989; SPANO & MELONI, 1992).

The Pirri sandstones crop out to the north of and in Cagliari town. It is composed by sandstones with, sometimes, conglomerate layers. This formation indicates a regressive phase of the sedimentation, marking the transition from bathial of the Gesturi marls and Fangario clays to littoral environments. A brief hiatus of sedimentation characterizes this transition, how testified by clasts of Fangario clays within the Pirri sandstones (PECORINI & POMESANO CHERCHI, 1969; SPANO, 1989; ASSORGIA *et alii*, 1997). The age of this formation is attributable to Serravalian (CHERCHI, 1974; LEONE *et alii*, 1992; ASSORGIA *et alii*, 1997).

1.4.2.4.2.4 3° Miocene Sedimentary Cycle

The sediments attributed to the 3° Miocenic Sedimentary Cycle crop out mainly in the northern Sardinia. In the sourrounding areas of the Campidano graben they occur only in the Cagliari hills to the south and in the Sinis and Capo Frasca peninsulas to the north.

In the Cagliari area the Upper Miocene succession is known as Cagliari limestones (GANDOLFI & PORCU, 1967; CHERCHI, 1974). The base is composed by marl-arenaceous limestones strongly bioturbated ("Pietra Cantone" Auct.) that lie above the Pirri sandstones usually with marl-arenaceous facies that indicate a new marine transgression. The depositional environment can be referred to the circalittoral plane (LEONE *et alii*, 1992). The age of this deposits is Tortonian (PECORINI & POMESANO CHERCHI, 1969; CHERCHI, 1974; 1985; CHERCHI & TREMOLIÈRES, 1984). A clear erosional surface marks the transition to clayish limestones, bioclastic limestones and biocalcarenites ("Tramezzario" Auct.). The base is characterized by angular unconformity, slumps, synsedimentary faults and erosional surfaces, that show the basin instability. The depositional environment can be referred to infralittoral to circalittoral zones (LEONE *et alii*, 1992). The age of this deposits, achieved with the ^{86}Sr/^{87}Sr isotopic analysis method, is between 12.1 Ma and 11.7 Ma (BARCA *et alii*, 2005). The Miocenic succession finishes with limestones and bioclastic limestones with characters from biohermal to biostromal ("Pietra Forte" or "Calcare di Bonaria" Auct.). Inside it is characterized by erosional surfaces and unconformities, testifying that the instability of the basin was continuing. The depositional environment is littoral and infralittoral (LEONE *et alii*, 1992). The age can be referred certainly to the Tortonian, but, because of the similarity with the comparable formations in the Oristano area, a Messinian age can not be excluded (CHERCHI, 1985; LEONE *et alii*, 1992).

The Upper Miocene succession in the northwestern edge of the Campidano graben begin with the Capo San Marco Formation (PECORINI, 1972; CHERCHI, 1974; CHERCHI *et alii*, 1978), that crops out in the Sinis peninsula. It is composed by marl-silty clays and silty marls, with intercalated organogenic limestones. The depositional zone is sublittoral with transition to lagoon and marsh environments (CHERCHI *et alii*, 1978). The planctonic foraminifera and the nannoplankton suggest a Lower Messinian age for this sediments (CHERCHI, 1981; 1985), even though Middle-Upper Messinian age for this Formation is also proposed (CIPOLLARI, 1997). The top of the Capo San Marco Formation is characterized by a paleosol that seals an erosional surface.

Above this paleosol lies the "Calcari laminati del Sinis" (CHERCHI *et alii*, 1978), that is an evaporitic formation composed by pure limestones. The depositional environment is mainly lagoon, alternated with brief marine sedimentation. The age is Messinian becouse of the stratigraphic position (CHERCHI *et alii*, 1978).

The Upper Miocene succession here continues with epineritic deposits that evolve rapidly again in evaporitic facies of th "Calcari di Torre del Sevo" (CHERCHI *et alii*, 1978). This deposits are composed by alternated littoral sandstones, siltitic clays and marl limestones. Upward follow limestones and dolomitic limestones. The depositional environment is mainly evaporitic. The age of this deposits can be referred to Messinian because lie above the "Calcari laminati del Sinis" and preceding the Lower Pliocene marine deposits (CHERCHI & MARTINI, 1981).

1.4.2.5 Pliocene Sedimentary succession

After the regression related to the Messinian Salinity Crisis, a new transgression affected the Sardinia during the Lower Pliocene. This sediments have been detected only in a small outcrops in the Capo Frasca and Sinis (Capo San Marco) peninsulas, and constitute the Nuraghe Baboe Formation (SPANO, 1989).

At the base of the Pliocenic succession of Capo San Marco, thick about 30-40 m, crops out a discontinuous breccia, composed mainly by Messinian, but also by Lower Miocene, Eocene and Paleozoic rocks (CHERCHI, 1973; CHERCHI *et alii*, 1978). Upward follow sandstones, arenaceous-siltitic clays, marls and clayish-arenaceous limestones. The fossils allow to refer this succession to Lower Pliocene (*Globorotalia margaritae margaritae* zone) (PECORINI, 1972; CHERCHI, 1973; CHERCHI & MARTINI, 1981; CHERCHI *et alii*, 1985; SPANO, 1989). The depositional environment is initially coastal then evolves towards deeper sea.

The small outcrop in the Capo Frasca peninsula, 50 m thick, is composed mainly by a clastic succession of littoral to intertidal depositional environment (ASSORGIA *et alii*, 1983).

Tectonic activity and strong erosion preceded the Lower Pliocene transgression. In fact, this sediments lie unconformably above the Lower Messinian in the Capo San Marco paninsula and Middle Miocene in the Capo Frasca peninsula. The Lower Pliocene successions is truncated to the top by an erosional surface, sealed by paleosols (Capo Frasca) or basaltic lava flows (Capo Frasca, Capo San Marco).

Sometimes just below the basaltic lava flows in the Sinis peninsula crops out a formation composed by conglomerates with pebbles of quartz and Paleozoic metamorphites and silty sandstones of fluvial-deltaic environment. This deposits have been correlated in the "Foglio 528-Oristano" of the Geologic Map of Italy with the Nuraghe Casteddu Formation (MASSARI & DIENI, 1973) that crops out in the eastern Sardinia near Orosei. This Formation is Middle Pliocene in age.

According to PECORINI & POMESANO CHERCHI (1969), in the eastern-southern Campidano plain crop out the Samassi formation, that constitutes the Pliocenic sedimentary filling of the Campidano graben. This formation is depicted as a chaotic sedimentary complex, composed by silty marls and sandstones, with the occurrence of conglomerate layers. The pebbles are consitued by Miocenic marls and Paleozoic rocks. The reworked fossils of several ages from the Aquitanian till Lower Pliocene (*Globorotalia margaritae*) and the stratigraphical position, allow to consider for the base of the Samassi formation an age following the Lower Pliocene and Quaternary for the upper part. MARINI *et alii* (1979) and MARINI MURRU (1981) indicate outcrops of the Samassi formation below the Pliocenic basaltic lava flows of the Gesturi plateau and in the southeastern edge of the Campidano graben near the village of Sinnai respectively, extending thus the the areas where the Samassi formation crops out eastward. The outcrop below the Gesturi plateau allows to consider the top of the Samassi formation not older than 3 Ma.

1.4.2.6 Quaternary deposits

The new geological surveys realized for the CARG Project show that the outcrops considered Samassi formation in the Campidano plain are Upper Pleistocene alluvial deposits (PATTA, 2003; BARCA *et alii*, 2011). Thus, in the Campidano plain crop out only deposits Quaternary in age. The oldest Quaternary deposits have been detected in the Campidano of Oristano. Here, the Faro Synthem, characterized by fine gravel of coastal environment, lies unconformable above the Pliocenic basalt lava flows. The age of the Faro Synthem is ?Upper Pliocene-Middle Pleistocene. Above this occurs the Serra de su Pranu Synthem, composed by aeolian sandstones with fossils of *Bovidae* and pulmonate Gastropods, Middle Pleistocene in age. The Upper Pleistocene deposits is constitue, along the entire Campidano plain, by the Portovesme Synthem, that is divided into two sub-Synthem: the first composed primarily by alluvial deposits, undergoing pedogenesis or terracing (Portoscuso sub-synthem) and the second matches with the "Panchina Tirreniana" Auct. (Calamosca sub-synthem).

The other Quaternary deposits outcropping in the Campidano plain are Holocene in age.

1.4.3 Tectonics

The Campidano graben structuring is included into the Cainozoic and Plio-Quaternary general tectonic evolution of Sardinia. The most important structures originate from Oligocene compression and Miocene and Plio-Quaternary extensional tectonics, related respectively to the collisional margin of northeastern Corsica and the opening of the Balearic basin and Tyrrhenian Sea. Till the sixties it was believed that the compressional tectonics in Sardinia was related only to the Variscan orogeny, while was known the importance of the Miocenic extensional tectonics. Some authors and have highlighted strike-slip faulting during Tertiary (ALVAREZ & COCOZZA, 1974) and thrusting of the Palaeozoic basement above the

Mesozoic covers (CHABRIER 1967; 1970). These structures were initially related to the Pyrenean-Provencal tectonics, but, depending on the occurrence of the reworked nummulites in synsedimentary deposits (the Cuccuru 'e Flores conglomerates, DIENI & MASSARI (1965) and ALVAREZ & COCOZZA (1974) suppose a younger age, probably Oligocene. Thus, the Oligo-Aquitanian strike-slip tectonics can be related to the Cenozoic continental collision between the Apulian plate and the south European margin (CARMIGNANI *et alii*, 1992; 1994; PASCI, 1997). The northern Sardinia is characterized by sinistral and compressional strike-slip tectonics, to which is related transtensional basins NE-SW oriented. On the other hand, the southern Sardinia is characterized by dextral and extensional strike-slip faults, with related sedimentary basins oriented NW-SE, reactivated during Plio-Quaternary times. The strike-slip tectonics has been active surely until the Upper Aquitanian, in fact, these faults and the associated basins are affected by the structuring of the Upper Burdigalian extensional basins (OGGIANO *et alii*, 1995). In the Sulcis-Iglesiente block the extensional reactivation of the strike-slip faults is shown. The main structural features of this area are the Narcao basin and the Cixerri trough. These basins are characterized by the stratigraphic succession of the Lower Eocene covered by the Cixerri Formation and Oligo-Miocene volcanics. These structures are oriented E-W and are traditionally interpreted as graben delimited by E-W normal faults. Actually, the structural lows of Cixerri and Narcao are gentle synclines with E-W axial trend that originated the depocentres for the sedimentation of the Cixerri Formation (CARMIGNANI *et alii*, 2004; FUNEDDA *et alii*, 2009). The Upper Burdigalian-Langhian ignimbrites are not affected by these folds, thus the upper limit of the compressional tectonic can be determined. These two synclines are related to a N-S shortening and the relationships with the NW-SE Plio-Quaternary troughs of Campidano and Gulf of Palmas suggest that these troughs originated by dextral strike-slip faults reactivated as normal faults during Middle Miocene and Plio-Quaternary times (Fig.1.4) (CARMIGNANI *et alii*, 2001). In the Upper Burdigalian, the strike-slip became extensional. During this period in the western margin of the Island a prograding westward sedimentary prism formed. Locally, it lies above the Oligo-Miocene volcano-sedimentary succession and is truncated upward by the Messinian erosional surface (LECCA *et alii*, 1997). Deposits of Upper Burdigalian-Langhian (2° Miocene Sedimentary Cycle) crop out in the northern Sardinia in the Logudoro continuing in the sea in the Gulf of Asinara, while in the southern Sardinia they crop out in Trexenta and Marmilla. These deposits are separated from the Miocene sedimentary prism in the western shelf of the Island by structural highs of Palaeozoic basement: Sulcis-Iglesiente-Arburese block, Malu Entu rise (LECCA *et alii*, 1986), in the offshore of Oristano, and Nurra and Asinara island to the north. These structural highs are horsts bounded to the west by normal faults dipping westward and to the east by normal faults dipping eastward. The deposits of the 2° Miocene Sedimentary Cycle have emplaced inside semi-grabens bounded to the west by master faults dipping to the east, while, eastward, these deposits lie with onlap geometry above the Palaeozoic basement and the Permo-Mesozoic covers. In northern Sardinia, it is easy discern the Oligo-Aquitanian strike-slip structures from the Burdigalian extensional structures, because they are perpendicular each other. In southern Sardinia it is more difficult because the younger extensional structures reactivate the older strike-slip structures, thus having the same trending. Between the 2° and 3° Miocene Sedimentary Cycle a sedimentary hiatus occurs, mainly evident in northern Sardinia where is marked by an angular unconformity (POMESANO CHERCHI, 1971; OGGIANO, 1987; MARTINI *et alii*, 1992). Probably, in southern Sardinia the same faults that have originated the semi-grabens during Middle Miocene, have been reactivated during Serravalian-Tortonian times, governing the deposition of the 3° Miocene Sedimentary Cycle, as shown in the seismic profiles acquired in the western shelf of Sardinia (LECCA *et alii*, 1986). During Messinian time, according to LETOUZEY *et alii* (1982) a N140°-160° oriented shortening phase occurred, producing an inversion tectonics that reactivated the Oligo-Miocene NW-SE faults. The effects of this Messinian tectonic inversion increase progressively southwards. In the northern Campidano there is minor evidence of Messinian structures, documented only at micro-scale, while in the southern Campidano several types of meso-scale and macro-scale structures can be related to this tectonic event (CASULA *et alii*, 2001). During Plio-Pleistocene, consequently to the opening of the south Tyrrhenian basin, new extensional phase causes the structuring of the Campidano graben that will be described in detail in the next paragraph. N-S trending faults developed, but, again, NW-SE trending faults were reactivated and appear the main structures.

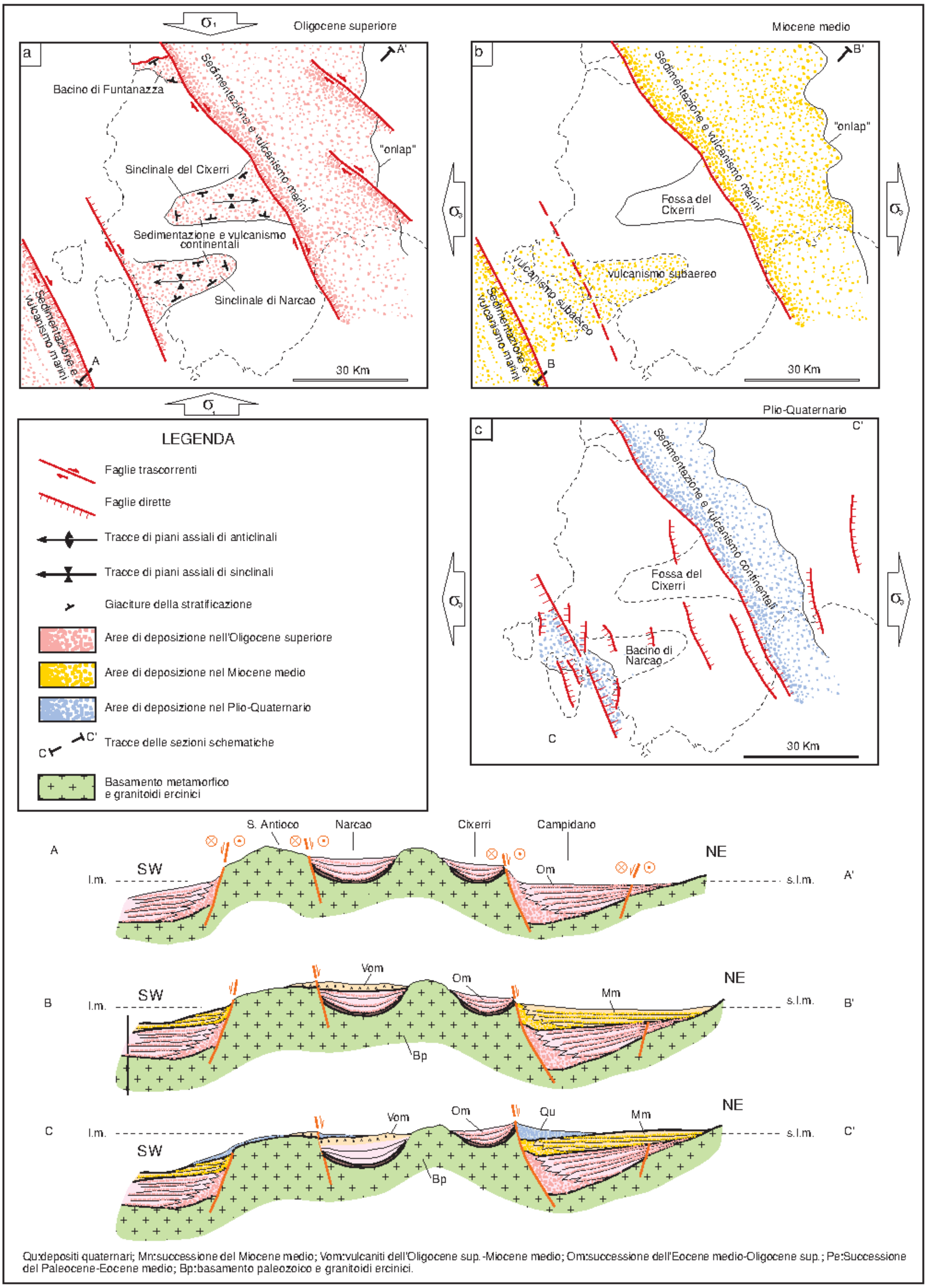


Fig.1.4- Tectonic-sedimentary evolution of SW Sardinia (CARMIGNANI *et alii*, 2001). a) Upper Oligocene; b) Middle Miocene; c) Plio-Quaternary.

In addition to the evidences of Plio-Pleistocene tectonics in Sardinia above mentioned, for the Campidano and surrounding areas the studies on neotectonics performed in the eighties (CHERCHI *et alii*, 1978a; 1978b; 1979; MARINI & MURRU, 1983) allowed to define several tectonic steps for the southern, central and northern Campidano. The main results are that the western fault that bounds the Campidano graben is active along the entire edge from 6.2 Ma (Upper Messinian) to 0.18 Ma (Middle Pleistocene). The eastern fault, on the other hand, is active in the same range of time only in the central and in the southern Campidano, where bounds the Cagliari hills, while in the northern Campidano is considered certainly active in Pleistocene time, but is not sure that was active in previous time.

1.4.4 Structural setting

The gravity, magnetic and seismic surveys, and some drilling carried out in the Campidano plain for geothermal and hydrocarbon research purposes allowed to increase the knowledge of the sub-surface tectono-sedimentary setting of the Campidano graben.

Three wells were drilled by SAIS: in the northern Campidano, in 1961, the Oristano 1 well, located in Casa Sassu locality (N 30°49'40", W 3°52'30") and in 1963 the Oristano 2 well, located in the northeastern edge of the Campidano plain, around 1 km to the south of Riola Sardo village (N 39°59'20", W 3°55'10"). In the southern plain the Campidano 1 well, drilled in 1964, is located near Villasor village (N 39°22'25", W 3°30'00"). A fourth well, Marcella, was drilled in the 1974 by AGIP in the offshore of Pula. The Oristano 1 well, deep 1802 m, among the for wells is the only one that does not reach the Oligo-Miocene volcanic succession because it stops within the Aquitanian marls. The stratigraphic succession based on the studied of POMESANO CHERCHI (1971), can be summarized: from 0 to 360 m, clayey-sandy pebbly alluvional deposits occur, with two marine levels, probably Tyrrhenian in age, interbedded between 7 and 33 m, and basaltic flows between 306 and 322 m. From 360 to 640 m a marly-siltitic continental complex, sometimes with pebbles of Paleozoic, Oligo-Miocene volcanics and Miocene marls, occur. This complex is ascribed to the Samassi formation (PECORINI & POMESANO CHERCHI, 1969). The base of this complex is separated from the underlying succession by an erosional surface. From 640 to 820 m marly-arenaceous marine sequence occur. The *Globorotalia crassaformis* planktonic foramininifera zone allow to refer the sequence from 640 to 730 m to the Middle Pliocene, whereas the *Globorotalia Margaritae* and *Globorotalia puncticulata* zone allow to refer the sequence from 730 to 820 m to the Lower Pliocene. The succession from 820 to 870 m is characterized by sandy-pebbly sediments with some fine sandy-marly intercalation. The planktonic foraminifera indicate the *Dutertrei-eggeri multiloba* zone (Lower Messinian). From 870 to 1802 m a marly-siltitic succession occurs Aquitanian to Tortonian in age. From 1403 m to the bottom of the well, basic volcanic rocks occur which can be related for both age and facies to the volcano-sedimentary layers interbedded within the Marmilla Formation.

The Oristano 2 well is deep 1700 m. The study of the well cores made by TILIA ZUCCARI (1969) allows to summarize the stratigraphic succession, characterized from 0 to 275 m by fluvial-lacustrine and lagoon-deltaic continental sediments, that can be referred to Quaternary. From 218 to 243 m basaltic flows occur. From 275 to 671 m a predominantly continental complex, clayey-sandy, occurs, with occasional content at some levels (380-385) of reworked Miocene microfaunas, mainly Tortonian in age. This complex can be ascribed to the Samassi formation too. From 671 to 729 m the succession is characterized by marine marly-clayey sequence, sometimes sandy of littoral environment with benthonic microfauna and rare planktonic foraminifera Lower-Middle Pliocene in age. From 729 to 856 m a sandy-clayey continental complex, probably Messinian in age occurs. From 856 to the bottom of the well at 1700 m, only andesites and ignimbrites of the Oligo-Miocene volcanic succession occur, except for the level from 1298 to 1308 m that is characterized by gravel with oysters (Upper Oligocene-Lower Miocene).

The stratigraphy of the Campidano 1 well has been studied by PECORINI & POMESANO CHERCHI (1969). The succession is characterized from 0 to 40 m by sandy-pebbly alluvional sediments referred to the Quaternary and from 40 to 540 m by a thick pebbly-siltitic complex that is referred to the Middle-Upper Pliocene (Samassi formation). In fact, within the conglomerates, pebbles of Miocene and Lower Pliocene occur.

Like in the Oristano 1 and Oristano 2 wells, the bottom of the Samassi formation is characterized by an erosional surface, that here lies directly above the Miocene succession and not on the Lower Pliocene marine sediments as in the northern Campidano. From 540 to 1162 m the succession is composed by the Miocene marine succession. The planktonic foraminifera zones allow to refer this succession to a time interval between Aquitanian and Tortonian. A 12 m thick pomiceous-sanidine tuffaceous layer occurs at 904 m. From 1162 to the bottom of the well at 1700 m only the andesites of the Oligo-Miocene volcanic complex occur, except for the red-purple conglomerate that occurs between 1564 and 1686 m, referred to the Ussana Formation.

Marcella is the deepest well drilled, reaching 2456 m. Based on the data of PALA *et alii* (1982) and CHERCHI & MURRU (1985), it shows a stratigraphic succession similar to that of the Campidano 1, with Pleistocene deposits from 154 to 245 m; quartz sands intercalated with clay levels and siltitic-sandy clays (Samassi formation) from 245 to 350 m; marly-calcareous complex that can be correlated with the "Tramezzario" and "Pietra Cantone" of the Cagliari Limestones from 350 to 522 m; sandstones that are correlated with the Pirri Sandstones (Serravalian) that lie below the Cagliari Limestones from 522 to 600m; marls with sandy layers correlated with the Fangario clays (Langhian-Serravalian) from 600 to 701 m; sandy-siltitic marls, marly-siltitic clays with interbedded sandy and conglomeratic layers, correlated with the Gesturi and Ales marls, from 701 to 1265 m; brownish-reddish sandy-clayey continental complex correlated with the Ussana Formation from 1265 to 1785 m; andesites of the Oligo-Miocene volcanic complex from 1785 to the bottom of the well at 2456 m.

Furthermore, several wells have been drilled for hydrogeological purposes, reaching maximum depth of a few hundred meters. In the northern Campidano, some of these wells stop when reach the Plio-pleistocene basalt lava flows, others stop in the Quaternary deposits (Cassa per il Mezzogiorno, progetto speciale N.25), like the majority of the wells drilled in the southern Campidano. However, some wells drilled close to the Quartu Sant'Elena reach, at 20-15 m depth, marine deposits ascribed to the Lower Pliocene (MURRU, 1983a). Another well, drilled 2 km to the west of Capoterra, crosses a marine-continental succession Middle Aquitanian to Middle Burdigalian in age (MURRU, 1983b). At first, the structural setting of the Campidano graben has been investigated and modelled with gravimetric and magnetic surveys, that show anomalies with the same trend of the Campidano plain, pointing out the probable occurrence of faults in both edges of the Campidano, which furthermore are located roughly along hydrothermal sources spring (TRUDU, 1953; 1961a; 1961b). The achievement of the gravimetric map of Sardinia (TRUDU, 1963; BALIA *et alii*, 1984; 1988) and other detailed gravimetric, magnetic and electrical surveys aimed at geothermal researches in the Campidano area (Fig.1.5) (FINZI-CONTINI, 1982; MARCHISIO *et alii*, 1982; CIMINALE *et alii*, 1985; BALIA *et alii*, 1984; 1990; 1991a; 1991b), allow to better modelling the structures characterizing the subsurface of Campidano and constructing several geological cross-sections throughout the graben using the stratigraphical data provided from the wells. Generally, these 2D models show that the Campidano is bounded in both the edges by almost vertical normal faults trending NW-SE and other vertical faults parallel to the axis of the graben (Fig.1.6). Consequently, the deepest part of the basin is its own centre. Furthermore, these models show that the thickness of the formations increases toward the centre of the graben. This is valid for the Oligo-Miocene volcanic complex, for the Miocene marine succession and for the Plio-Quaternary sediments.

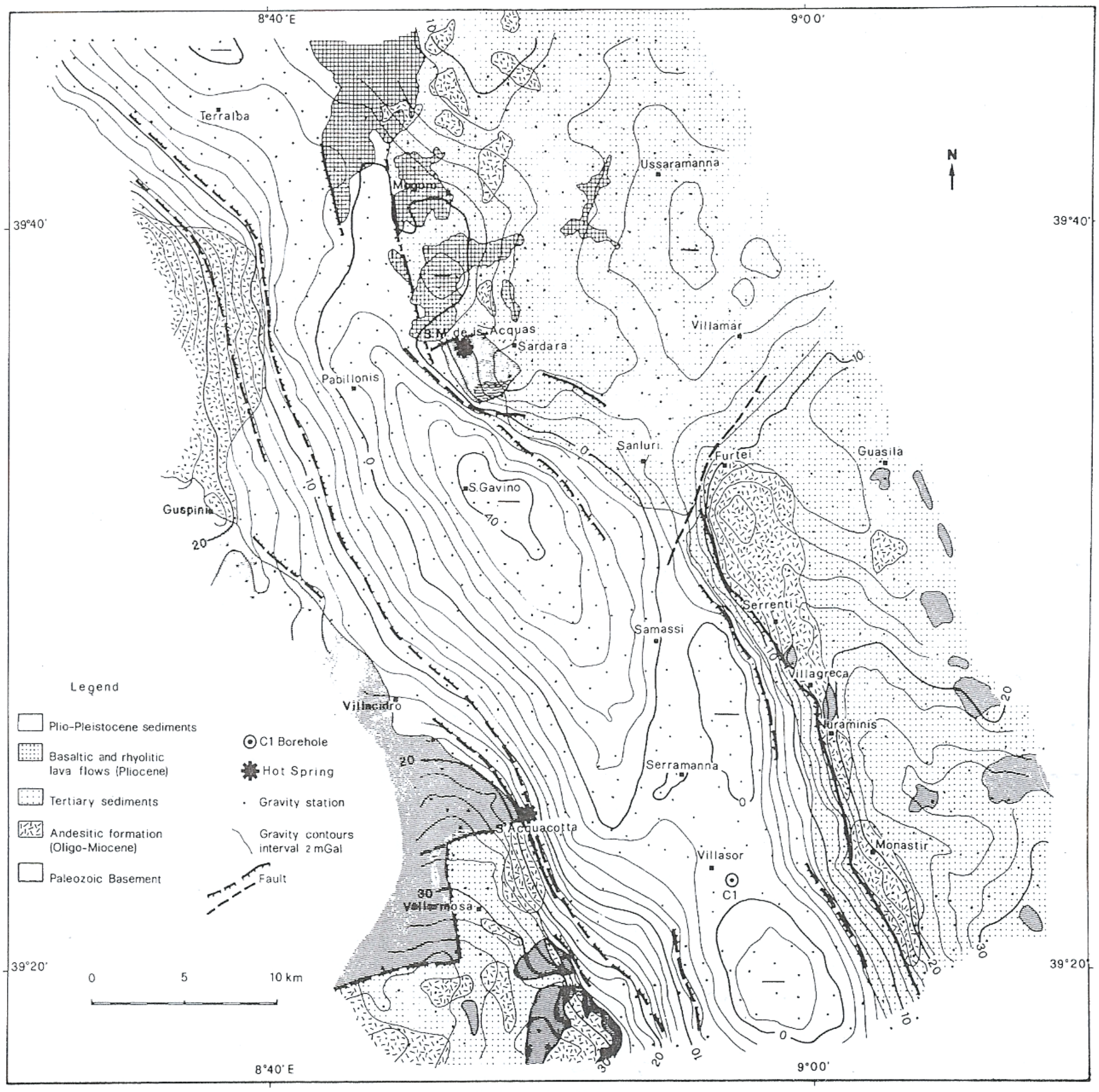


Fig.1.5- Bouguer anomaly map of the Campidano graben (from BALIA *et alii*, 1984).

Thus, for these Authors, the present area of the Campidano was a structural low already in the Late Oligocene, considering the age of the volcanites and marine sediments crossed by the deep wells described above. Another geological cross-section, obtained by Balia *et alii* (1991c) using combined magnetotelluric, gravity, electrical and magnetic geophysical data, shows that the faults bounding the Campidano graben between Vallermosa and Monastir (southern Campidano) are not vertical (Fig.1.7).

The seismic data acquired in the Campidano plain by SAIS in 1960-1961 and AGIP-PROGEMISA in 1991-1992 and in the offshore of Cagliari by AGIP in the 1970 have been interpreted and partly published by CASULA *et alii* (2001) that in this ways offers the more recent interpretation of the study area.

Starting from the seismic interpretation, CASULA *et alii* (2001) realise drawn a structural sketch map (Fig.1.8) where the structures are discerned depending on the period when were active, and proposed several geological cross-section throughout the Campidano from the offshore of Cagliari to the Gulf of Oristano and block diagrams that depict the structural setting of the Campidano area in Upper Oligocene-Burdigalian, Messinian and Plio-Quaternary (Fig.1.9).

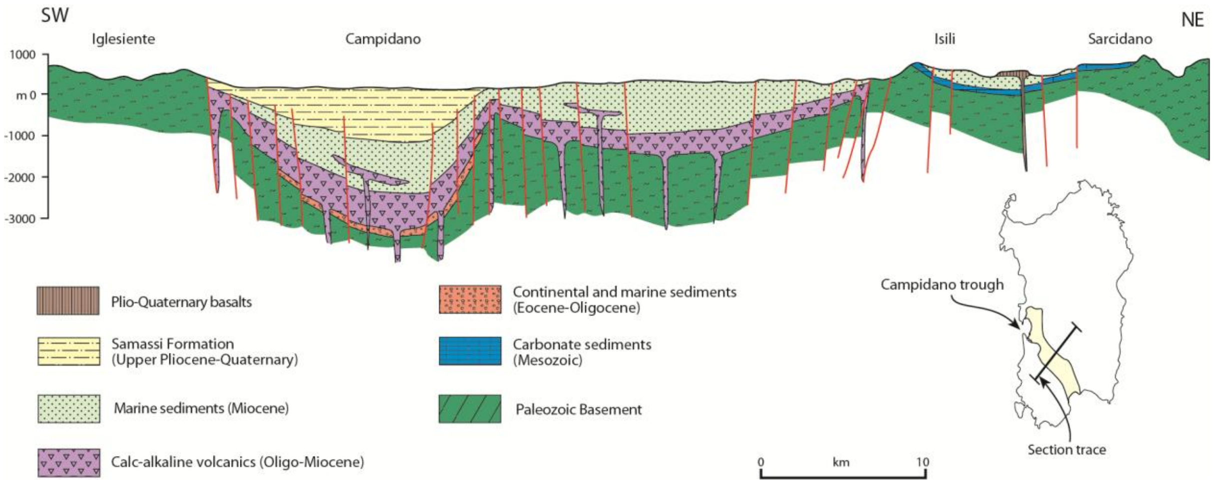


Fig.1.6- Geological cross-section across the Campidano graben, based on aeromagnetic data interpretation (modified from BALIA *et alii*, 1991b).

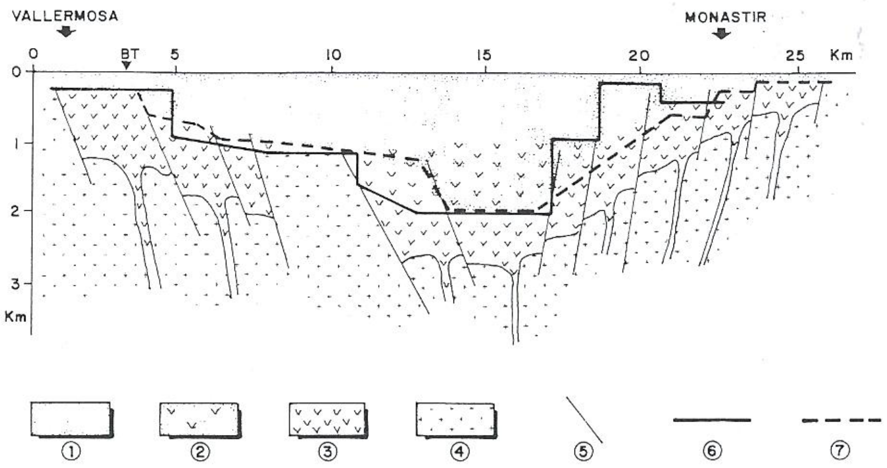


Fig.1.7- Geophysical-geological section across the Campidano graben (BALIA *et alii*, 1991c). 1: Plio-Quaternary sediments; 2: Oligo-Miocene volcano-sedimentary succession; 3: Oligo-Miocene andesites; 4: Paleozoic basement; 5: faults; 6: limit between high and low conductivity rocks; 7: limit between rocks with density contrast less than zero and greater or equal to zero.

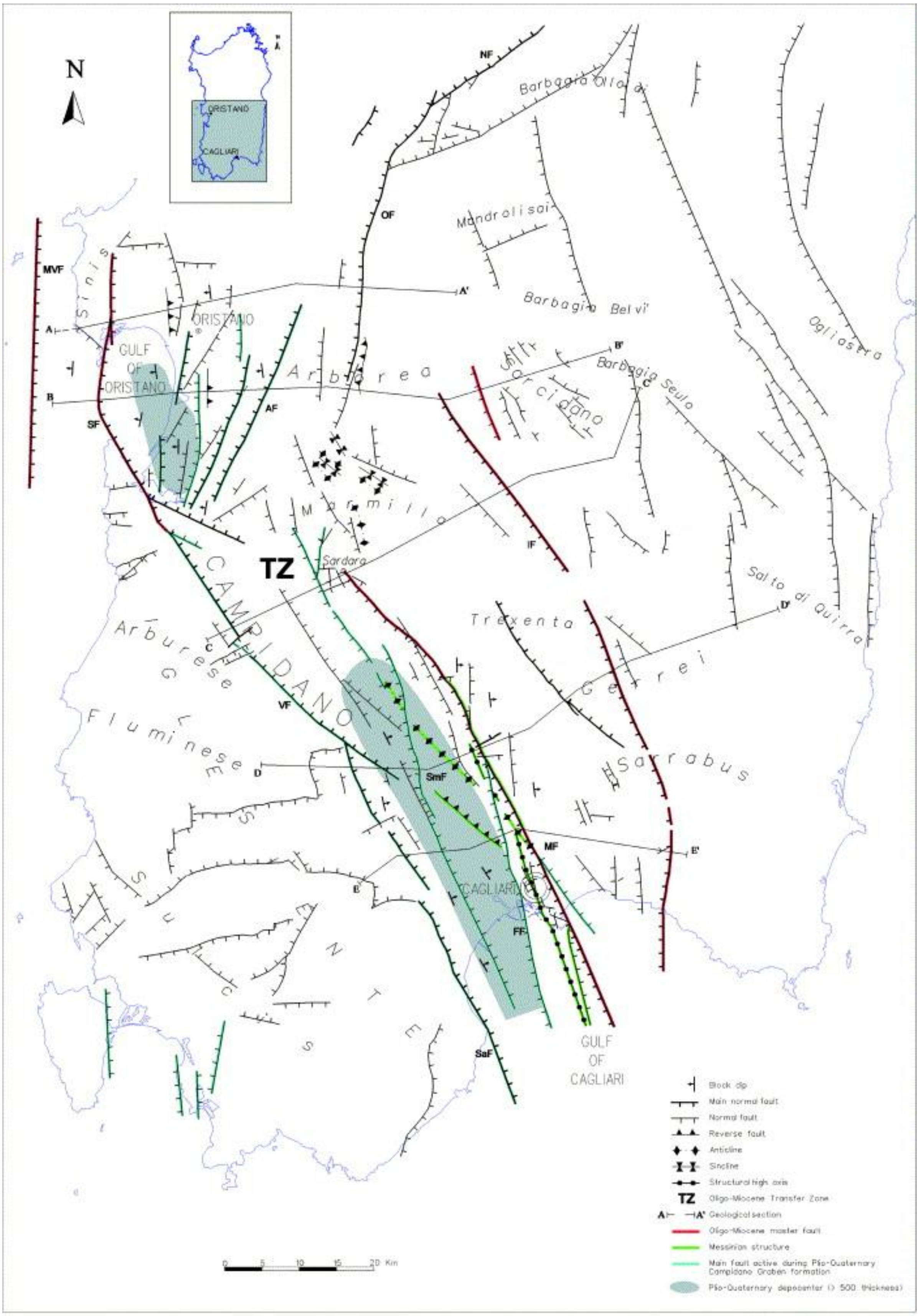


Fig.1.8- Structural sketch map of the southern Sardinia accordin to CASULA *et alii* (2001).

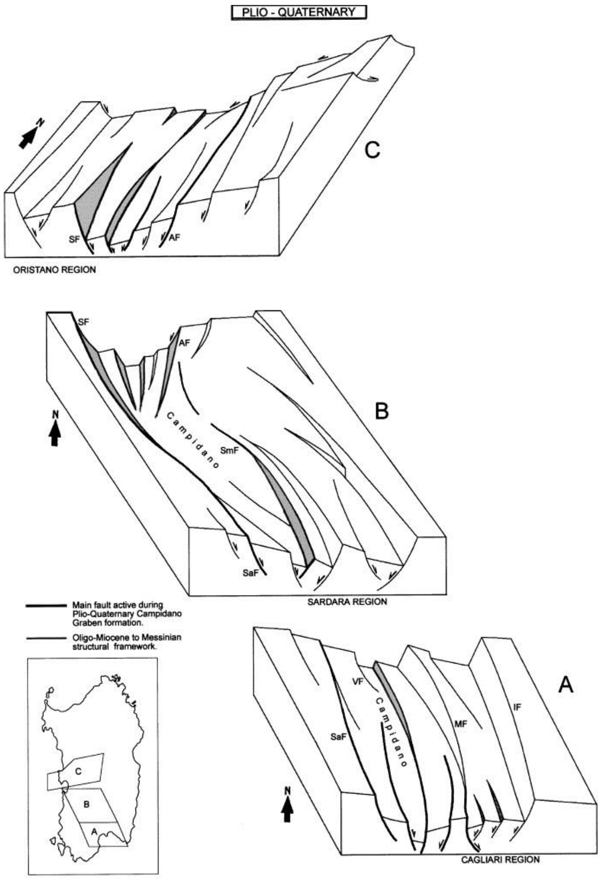


Fig.1.9- Schematic block diagram of the Plio-Quaternary structure in the Campidano area (CASULA *et alii*, 2001).

These Authors divide the Campidano into three parts, that are, from north to south, Oristano region, Sardara region and Cagliari region. The Oristano region is a half-graben bounded by an east-dipping and N-S trending normal fault located to the east of Capo Frasca and Sinis peninsula (Fig.1.9c). The related monocline is characterized by several antithetic faults trending roughly NNE-SSW. The master fault was active both in Oligo Miocene and Plio-Quaternary times. The southern Campidano was a half-graben bounded to the east by a master fault dipping to the SW and trending NW-SE parallel to the graben axis (Fig.1.9a). The main fault active during Plio-Quaternary time bounds, on the contrary, the western edge of the Campidano graben, striking still NW-SE but dipping to the NE. Between the Oristano region and the Cagliari region, the 40 km long transfer zone in the Sardara region occur (Fig.1.9b). The structural high in the Sardara region is interpreted as "horst-type twist-zone" located between the two Oligo-Miocene master faults with contrary dip direction in the northwestern and southeastern of the Campidano. CASULA *et alii* (2001) point out, furthermore, inversion structures related to Messinian N140-160° shortening phase. As a result, the main NNW-SSE Oligo-Miocene longitudinal faults were reactivated as reverse faults and related folds developed. These structures are evident mainly in the southern Campidano, in fact, the effects of the Messinian tectonic inversion increase progressively southwards. In the northern Campidano the Messinian structures occur only at a micro-scale, while in the southern Campidano several kinds of meso-macro scale structures can be related to this tectonic event. The Plio-Quaternary faults are clearly inherited from previous stages of deformation. The maximum thickness of the Plio-Quaternary (500-600 m) sediments occurs in the central part of the graben. For the Authors, the important throws of Plio-Quaternary faults are however less than those of the Oligo-Miocene ones.

Thus, as regards the Plio-Quaternary tectonics affecting the Campidano graben, up to now, no estimation of the extension and paleostress orientation have been made. Furthermore, the models proposed until now, show geometrical inconsistencies and are not aimed to the understanding and definition of the Plio-Quaternary evolution. In fact, to achieve consistent data concerning the extension values and the paleostress orientation it needs to have as starting point the more robust as possible geological model. It is clear that the detailed geometry of faults and surfaces plays an essential role in the evaluation of extension and paleostress orientation. For example, very different extension values we will obtain from the two geological cross-section showed in Fig.1.6 and 1.7, carried out between Vallermosa and Monastir. In fact, one of these shows almost vertical faults, assuming therefore that no horizontal extension occured in the Campidano graben, whereas the other one shows inclined faults that admit some extension. Furthermore, if restored, these sections show different structural setting. In the first one a folding event is supposed before the faulting, whereas in the second one the beds restored will be mainly horizontal. Other inconsistencies arise when perpendicular section are carried out.

The Fig.1.10 shows two geological cross-sections carried out between Villacidro and Villanovaforru (crossing the Campidano graben) and San Gavino and Villasor (parallel to the graben axis), crossing each other. The inconsistency is in the dipping of the faults, because is roughly the same in both the sections although they are cut with different orientation and an apparent dipping must be admitted. Actually, if the Campidano graben is characterized by NW-SE trending faults, the true dips of the faults can be appreciate only in the NE-SW cross-section, whereas in the sections parallel to the strike of the faults, the fault planes crossed by the section should be depict as roughly horizontal lines. Also the geological cross-sections obtained from the interpretation of the seismic lines show inconsistencies. For example, the

Fig.1.11 shows that, once in scale, the normal faults have dips less than 30°, reliable with an extension occurred at deeper structural level than that known for this are a that time.

To conclude, these models, with the inconsistencies that presents, can not be used to achieve the purposes of this work, making necessary to reinterpret the available data, mainly the seismic ones.

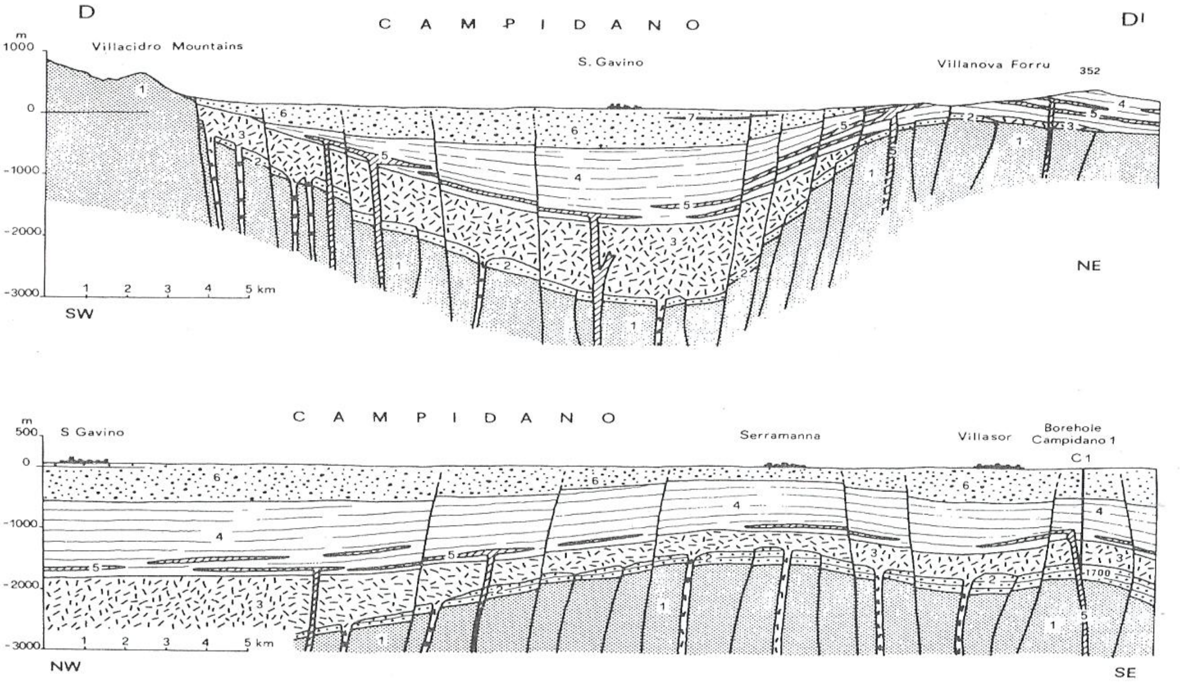


Fig.1.10- Geological cross-section across the Campidano graben (BALIA *et alii*, 1984). 1: Paleozoic Basement; 2: Eocene sandstones and clays; 3: Oligocene-Lower Miocene andesitic-tufaceous formations; 4: Upper Oligocene-Miocene-Lower Pliocene sediments; 5: andesitic lavas and tuffs; 6: Pliocene (Samassi formation) and Quaternary sediments; 7: Pliocene basalts.

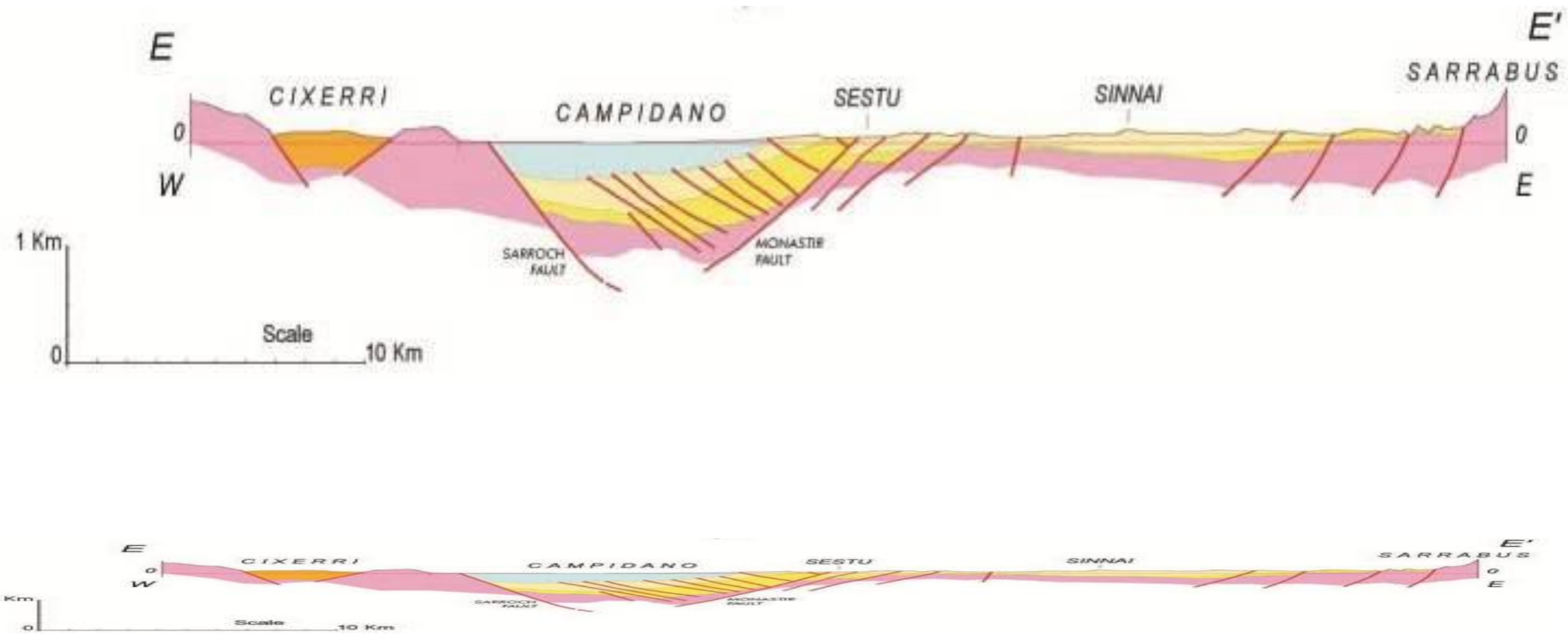


Fig.1.11- Above: geological cross-section across the Campidano graben to the north of Cagliari (CASULA *et alii*, 2001). Below: the same section without vertical exaggeration. Pink: Palaeozoic Basement; orange: Paleocene-Eocene; dark yellow: Oligo-Miocene syn-rift deposits; light yellow: Miocene post-rift deposits; pale-blue: Middle-Upper Pliocene-Quaternary sediments.

1.5 GEODYNAMIC SETTING

The Sardinia continental block is located in the centre of the Western Mediterranean, surrounded by two Neogene ocean-floored basins: the Liguro-Provencal basin to the west, opened between 30 and 15 Ma (CHERCHI & MONTADERT, 1982), and the Tyrrhenian basin to the east, still evolving since roughly 10 Ma (intra-Tortonian) (KASTENS *et alii*, 1988; SARTORI, 1990).

Therefore, the structural setting of the Campidano graben, volcanic activity and uplift affecting the Sardinian crust in the latest million years, are obviously related to the geodynamic evolution of the Western Mediterranean and, in particular, to the opening of the south Thyrrhenian basin, that probably reactivates older structures related to the previous geodynamic settings.

1.5.1 Geodynamic of Western Mediterranean from Late Oligocene to Tortonian

The central-western Mediterranean is characterized by sub-basins (Alboran, Valencia, Provencal, Algerian and Tyrrhenian basins) which developed essentially during the last 40 Ma, that are younger from west to east (REHAULT *et alii*, 1984). Nevertheless, the eastern Mediterranean is older than the western because is floored by Mesozoic oceanic crust (ROBERTSON & DIXON, 1984).

The opening of these basins was related to the eastward retreating of the Apennine-Maghrebides subduction zone and located in the back-arc region. The arc migrated about 800 km eastward from the Late Oligocene to present (GUEGUEN *et alii*, 1998).

During the Oligocene, the southern Europe, in the area between the Iberian peninsula and southern France consisted of several terranes, nowadays located hundreds of kilometres away. Among these are the internal zone of the Betic-Rif Cordillera, the Balearic Islands, the Kabylies, Corsica, Sardinia and Calabria (Fig.1.12).

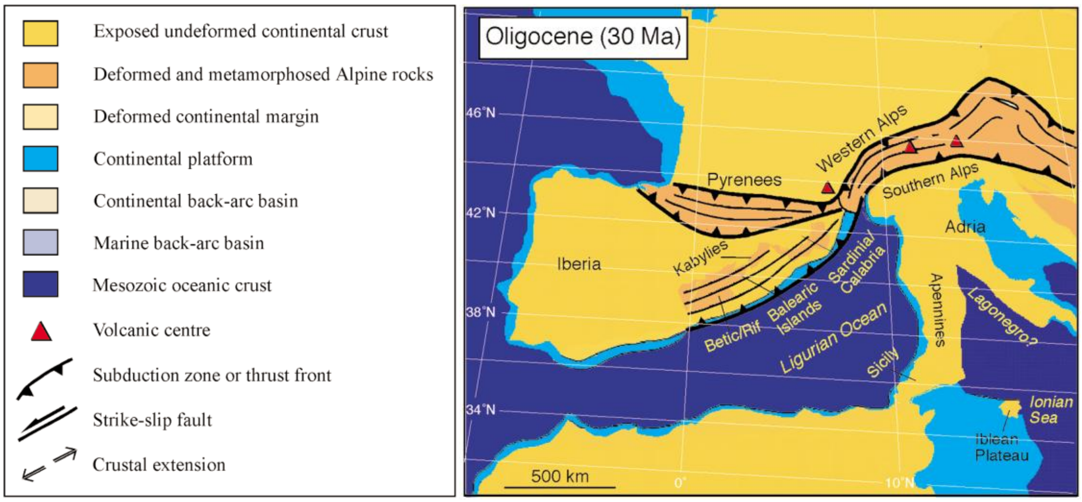


Fig.1.12- Oligocene reconstruction (30 Ma) of the Western Mediterranean (from ROSENBAUM *et alii*, 2002)

The present structural configuration of the Alpine suture in the western Alps and in northeast Corsica suggests that, prior to continental collision (the Alpine orogen underwent a major orogenic episode in the Early Oligocene), the area has been controlled by a southeast-dipping subduction system. In the late Oligocene, however, the polarity of the subduction system changed, and a new northwestern subduction system developed in the southern margin of the western Europe, producing calc-alkaline volcanism in Provence and Sardinia (ROSENBAUM *et alii*, 2002, and reference therein). Thus, the new subduction system and the related roll-back could have possibly triggered the opening of the western Mediterranean basins (Fig.1.13).

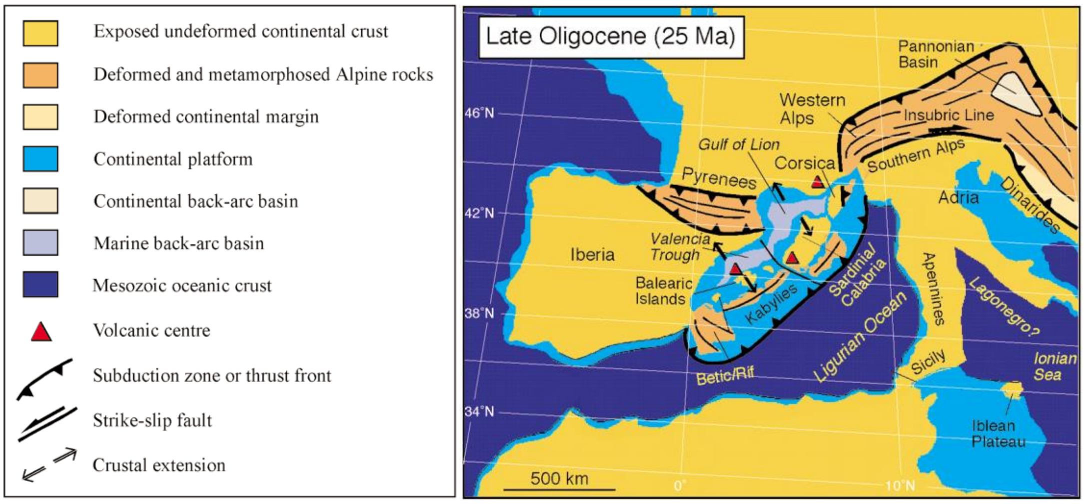


Fig.1.13- Late Oligocene reconstruction (25 Ma) of the Western Mediterranean (from ROSENBAUM *et alii*, 2002).

Furthermore, as a result of the subduction rollback, extension in the Early Miocene led to the rifting and drifting of continental terranes formerly attached to southern France and Iberia. Thus, during the opening of the Ligurian Sea and Valencia trough, the Balearic Islands, Corsica, Sardinia and Calabria were subjected to block rotations. Extension in Valencia Trough ceased 21-20 Ma ago while in the Gulf of Lion, tectonic activity ceased 20-18 Ma ago (CHERCHI & MONTADERT, 1982), possibly due to the collision of Corsica, Sardinia and Calabria with the Appennines (Fig.1.14). However, according to CHAMOT-ROOKE *et alii* (1999), the opening of the Liguro-Provencal Basin may have ceased as late as Late Burdigalian time (16.5 Ma) and the rotation of Sardinia was essentially complete by 15 Ma (GATTACECA *et alii*, 2007)

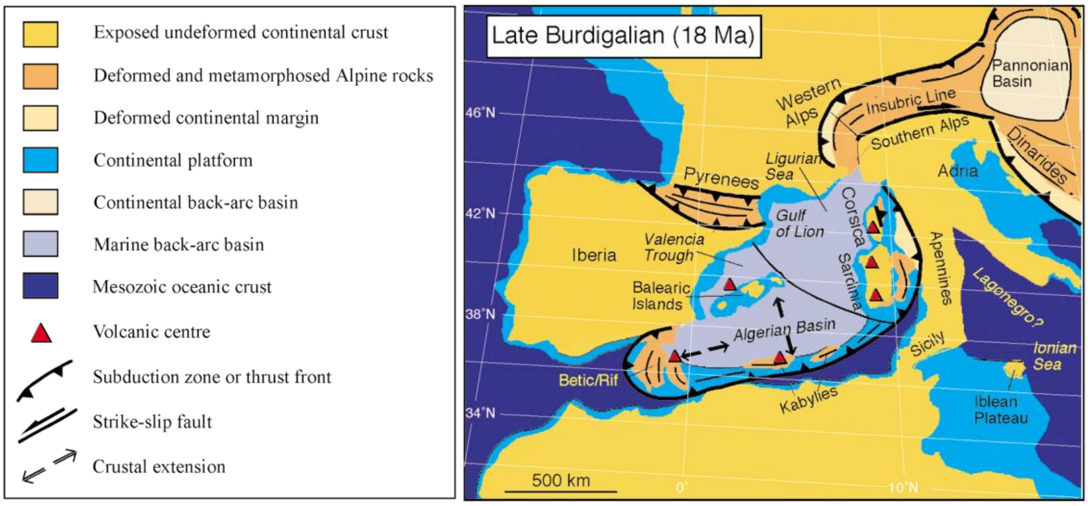


Fig.1.14- Late Burdigalian reconstruction (18 Ma) of the Western Mediterranean (from ROSENBAUM *et alii*, 2002).

Following collision, Apennine units arrived at the subduction system and impeded rollback, which led to the cessation of the back-arc extension in the Ligurian Sea and a relative quiescence between 18 and 10 Ma (ROSENBAUM *et alii*, 2002). In Tortonian times, therefore, most of the Western Mediterranean basin was already opened.

1.5.2 Tyrrhenian Basin opening

The Tyrrhenian Sea is the youngest and the easternmost basin of the boudinated backarc lithosphere in the hangingwall of the Late Oligocene to Present Apennines subduction, which started in the Provencal and Valencia troughs and progressively moved to the Algerian and

Tyrrhenian basins (Fig.1.15). The major lithospheric boudin is represented by the Sardinia-Corsica block (GUEGUEN *et alii*, 1997; 1998; DOGLIONI *et alii*, 2004). The opening of the Tyrrhenian Sea is the result of the southeastward rollback of the subduction system near the margin of the Adriatic plate, accompanied by coeval crustal shortening in the Apennines (MALINVERNO & RYAN, 1986), where thrust systems that propagated eastward occurred.

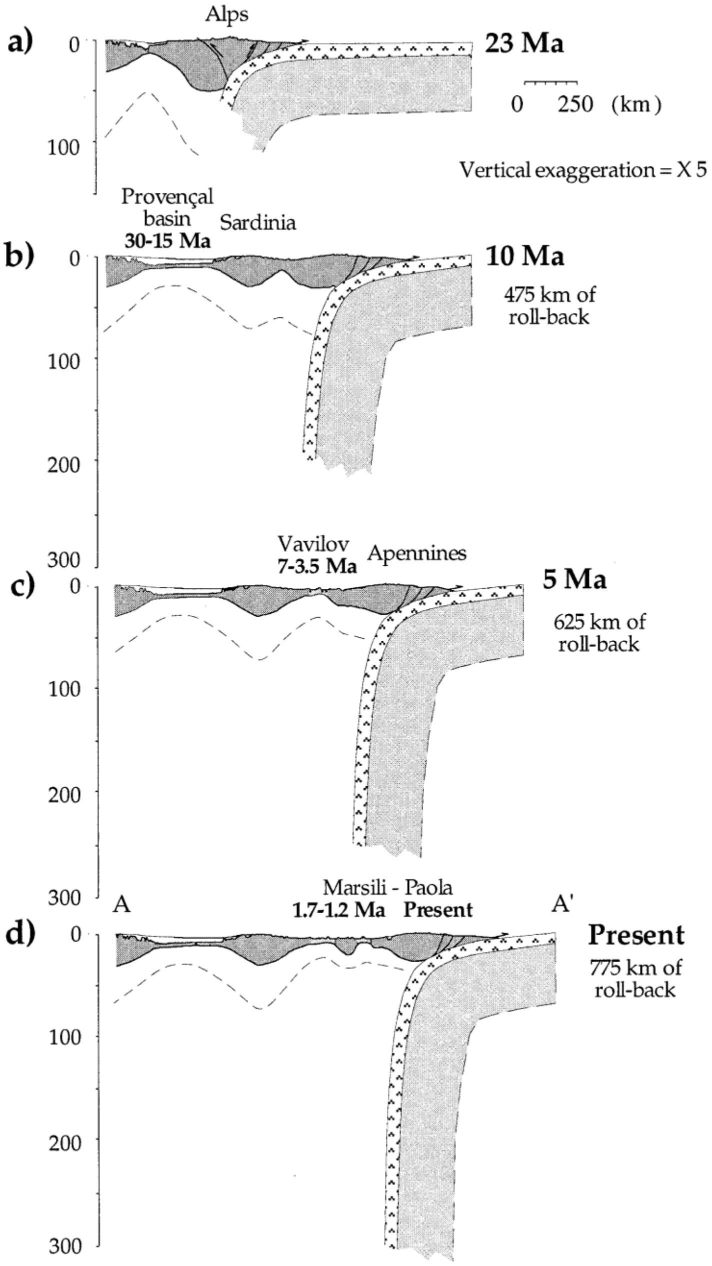


Fig.1.15- Balanced cross-section illustrating the evolution of the western Mediterranean and Tyrrhenian basin during the Neogene and Quaternary (from GUEGUEN *et alii*, 1997).

It is widely accepted that the opening of the Tyrrhenian basin occurred in three extensional phases, clearly differentiated in time: Upper Tortonian to Messinian, Messinian to Middle Pliocene, Middle Pliocene to Recent (SARTORI, 1989).

The first stage (Upper Tortonian to Messinian) is characterized by an extensional phase, roughly E-W trending, that affected mainly the northern Tyrrhenian basin (Fig.1.16).

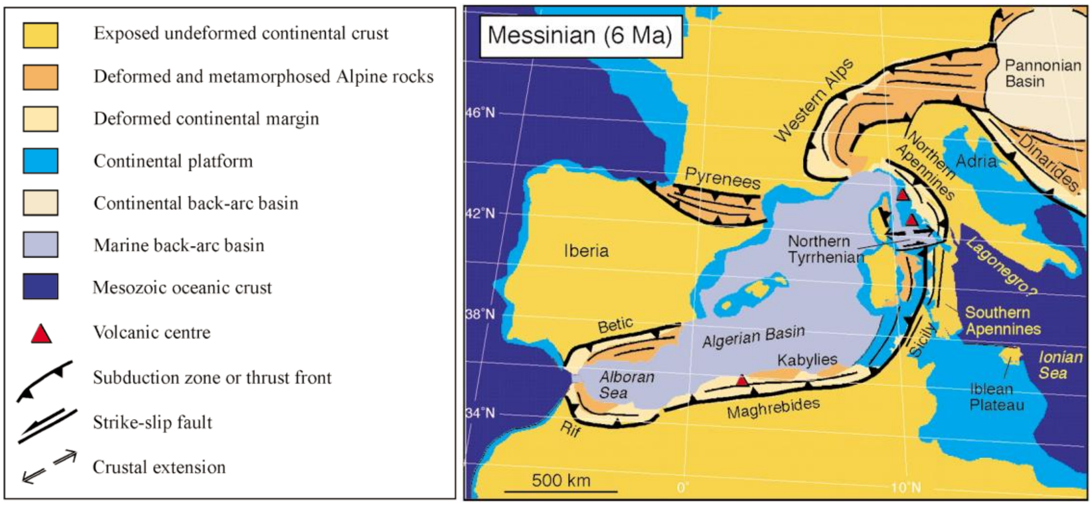


Fig.1.16- Messinian reconstruction (6 Ma) of the Western Mediterranean (from ROSENBAUM *et alii*, 2002).

The northern Tyrrhenian Sea, located between Corsica and northern Apennines to the north of the 41st parallel, that represents an important magnetic and tectonic feature, is shallow and its crust is only moderately thinned, compared with the southern Tyrrhenian. This is likely due to the difference on the amount of the minimum extension affected the northern (25 km) and the southern (253 km) Tyrrhenian basin (DOGLIONI *et alii*, 2004). Clearly, in the same time, also part of the present southern Tyrrhenian basin was affected by extensional tectonic, to which is related the formation of the eastern Sardinia margin. In fact, in the offshore Sardinia basin, located just to the east of the south of the Island and to the south of the Orosei Canyon Line (rougly 40th parallel), that is an inherited Mesozoic discontinuity reactivated as a transfer zone during the Neogene (SARTORI *et alii*, 2001), the youngest pre-evaporitic subunit (Late-Tortonian-Early Messinian in age) displays wedge-shaped reflectors, and forms the lower portion of a syn-rift complex including the Messinian and part of the Pliocene sediments (SELLI & FABBRI, 1971; FABBRI & NANNI, 1980; SARTORI *et alii*, 2001; 2004). Generally, in the western Tyrrhenian basin the faults are oriented N-S to N30° (FABBRI & NANNI, 1980; SARTORI, 1989, and references therein). During this time interval, rifted also the Cornaglia Terrace, a wide and flat area, that can be separated into a northern and southern sector across the Orosei Canyon Line. The northern Terrace is limited laterally by two prominent morphological elements: the Baronie Seamount to the west and the Selli Line, that is a deep-reaching east-dipping listric fault, also called Central Fault, to the east. This sector rifted from intra-Tortonian to intra-Messinian times (MASCLE & REHAULT, 1990; SARTORI *et alii*, 2004), while the southern sector, located between the Sardinia basin and the Major Seamount, rifted continuously from intra-Tortonian to intra-Pliocene (SARTORI *et alii*, 2001).

During the second stage (Messinian to Middle Pliocene), a strong crustal stretching affected the central Tyrrhenian basin. The Magnaghi basin is an area confined by the Magnaghi Seamount to the south, by the Selli line to the west and by the De Marchi and Farfalle Seamounts to the east. This basin rifted from intra-Messinian to intra-Pliocene times (MASCLE & REHAULT, 1990). The Vavilov basin (Fig.1.17) is an oceanic area of Pliocene age (MASCLE & REHAULT, 1990, SARTORI, 1990), showing a triangular shape. It is limited to the south by the Vavilov Seamount and by the D'Ancona ridge, to the west by the De Marchi and Farfalle Seamount and to the east by the base of the Campania continental slope. The age of the basalts of the oceanic crust in the Vavilov basin, achieved from both radiometric and biostratigraphic data, can be referred to a time interval between 6.4 Ma (Messinian) and 2.2 Ma (Gelasian). The age of the main volcanoes in this area, Magnaghi and Vavilov, except the Pleistocene rejuvenation of the Vavilov, is coeval with the bulk of magmatism in Sardinia, between 3 and 2 Ma. Furthermore, the Pliocenic volcanoes are aligned along a zone E-W trending and are located on fractures oriented roughly N-S, showing an E-W extension direction (SARTORI, 1986; 1989).

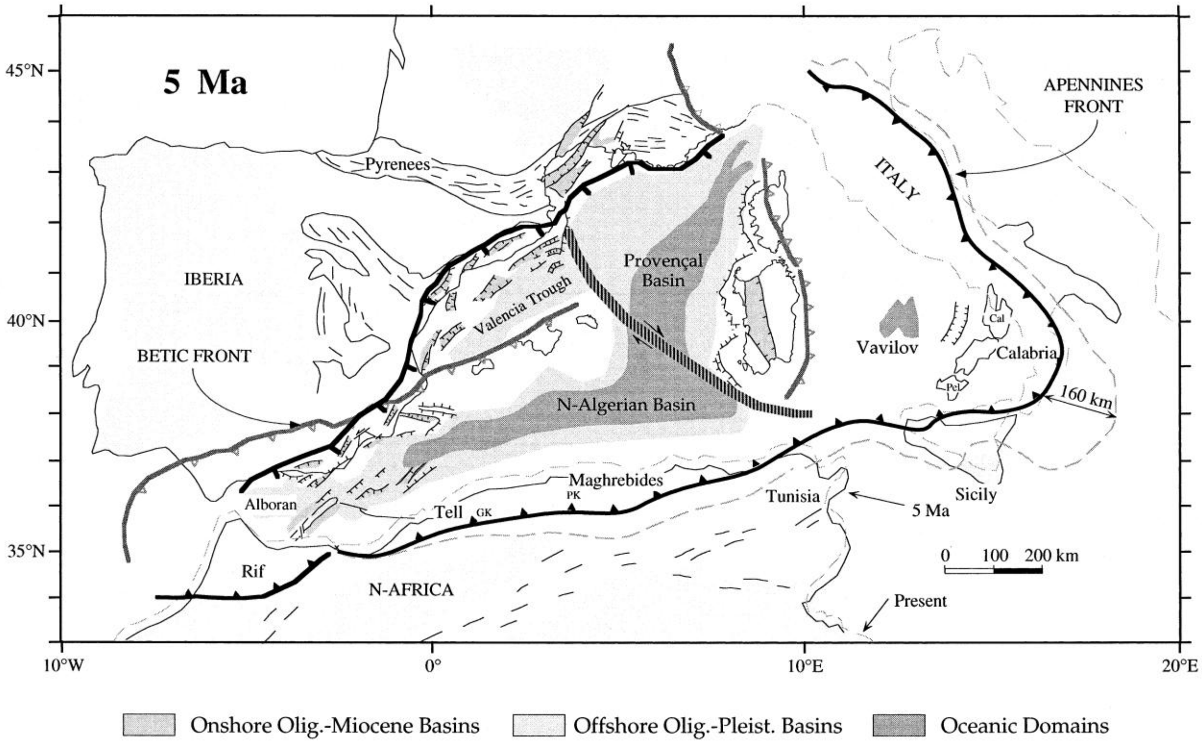


Fig.1.17- Early Pliocene reconstruction (5 Ma) of the Western Mediterranean (from GUEGUEN *et alii*, 1998).

During the third stage (Middle Pliocene to Recent), the crustal extension in the Magnaghi and Vavilov areas ceased, while in the southeasternmost Tyrrhenian, oceanic basalts related to crustal extension occurred in the Marsili basin (Fig.1.18) (KASTENS *et alii*, 1988; SARTORI, 1989; MANTOVANI *et alii*, 1996). The sediments just above the basalts are Lower Pleistocene in age (1.8 Ma) in agreement with biostrtigraphic and magnetostratigraphic datings (KASTENS *et alii*, 1987). The only radiometric dating available for the Marsili volcano indicates 0.2 Ma (Middle Pleistocene) (SAVELLI, 1984). During the Pleistocene-Holocene, simultaneously with the Marsili volcanic activity, other several volcanoes developed in the sourrounding areas: Etna, Ustica, the volcanoes in the Sicily Channel, the reactivated upper part of the Vavilov volcano and, in Sardinia, the Logudoro volcanic district (SARTORI, 1986, and reference therein). The geographic position of these volcanic areas, shows N110-130° direction, demonstrating a change of the extensional stresses from roughly E-W in Pliocene time to roughly N120° in Pleistocene time.

The lithosphere in the Tyrrhenian basin underwent rapid thinning and high extensional rates, related probably to the weakening of the lithosphere due to the previous compressive and extensional deformations that affected it (SARTORI *et alii*, 2004). The change in extensional rates between the opening of the Vavilov basin (Pliocene) and Marsili basin (Pleistocene), from 7-8 cm/yr to 19 cm/yr respectively, can be due to the reduction of the width of the slab, causing an increase of the roll-back velocity (GUILLAME *et alii*, 2010).

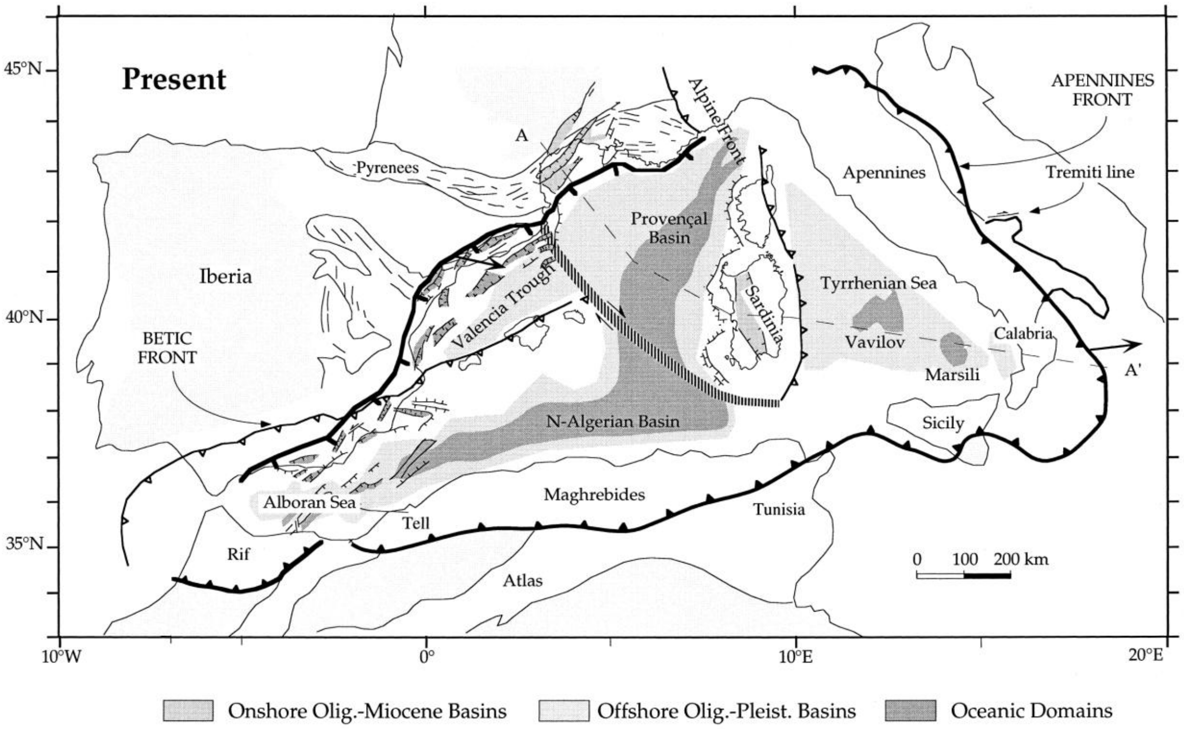


Fig.1.18- Present-day reconstruction of the Western Mediterranean (from GUEGUEN *et alii*, 1998).

1.5.3 Present-day structure of the lithosphere in Sardinia and surrounding areas

Informations on the physical and chemical properties of the lithosphere and astenosphere have been achieved by geophysical investigations and petrology-geochemistry studies of magmatic rocks. Several reconstructions of the Moho discontinuity isobaths, based on seismic data, have been proposed for the Italy and sourrounding areas. The Italian crust is generally continental, apart in the Tyrrhenian abyssal plain where a 10 km thick Plio-Quaternary oceanic crust occurs. Several different Moho discontinuities may be distinguished (Fig.1.19): a new forming Neogene-Quaternary Moho with low velocities in the Tyrrhenian basin and western Apennines (Tyrrhenian Moho), an old Palaeozoic-Mesozoic Moho in the Padano-Adriatic foreland areas (Adriatic Moho) and another Paleozoic-Mesozoic old Moho in the Alpine belt and Sardinia (European Moho) (SCROCCA *et alii*, 2003). Stable areas (Sardinia, Adriatic Sea and Puglia) have Moho depth at about 30 km while the crust is thicker underneath the Alpine belt (45-55 km) and is thinner in the Tyrrhenian Sea (10 km).

The thickness-map of the lithosphere (PANZA *et alii*, 1992; Fig.1.20), based on the analysis of the waves surface dispersion, shows that, in the foreland areas of the Tyrrhenian Sea, the lithosphere thickness varies from 70 km in the northern Adriatic Sea, to about 110 km to the southeastern in Puglia. In the Tyrrhenian Sea, lithosphere thickness thins to 20-30 km. Along the Alps belt the lithosphere thickness shows the higher values (up to 130 km in the western Alps). The Bouguer gravity anomalies map (Fig.1.21) shows a positive anomaly in Piemonte along the Ivrea-Verbano zone, the high positive anomaly that characterizes the Tyrrhenian Sea and the negative anomalies in the alignment of the Apennine foredeep. The heat flow values are very high (up to 200 mW/m^2) in the Tyrrhenian Sea and western Apennines, particularly in Tuscany, and decrease to 30-40 mW/m^2 in the foreland areas (Po plain, Adriatic coast and Ionian Sea) (Fig.1.22).

Several data concerning the thickness of the crust and lithosphere of the Sardinia-Corsica block have been proposed from several Authors using several methods (data and methods are summarized in Tab.1) (EGGER *et alii*, 1988; FINETTI, 2005; GVIRTZMAN & NUR, 2001; MORELLI *et alii*, 1967; 1976; MUELLER & PANZA, 1984; PANZA *et alii*, 1992; PANZA *et alii*, 2007a; 2007b; PANZA & RAYKOVA, 2008; SCARASCIA *et alii*, 1994; SCROCCA *et alii*, 2003; YEGOROVA & STAROSTENKO, 2002). Generally, the crust of Sardinia-Corsica block is considered 25-35 km thick and the lithosphere 60-80 km thick. Therefore, the

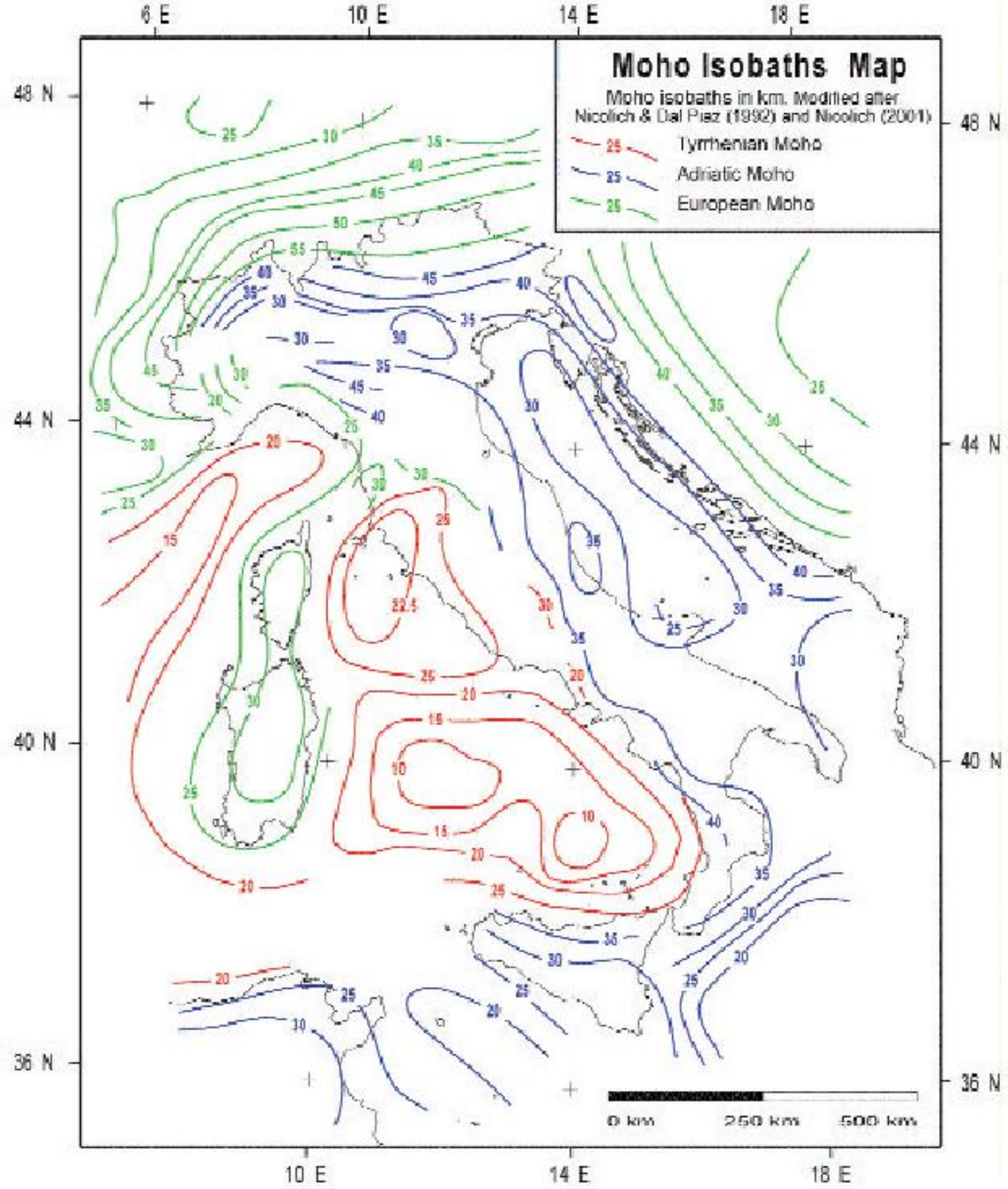


Fig.1.19- Moho isobaths map of Tyrrhenian Sea and sourrounding areas. Modified in SCROCCA *et alii* (2003) from NICOLICH & DAL PIAZ (1992) and NICOLICH (2001).

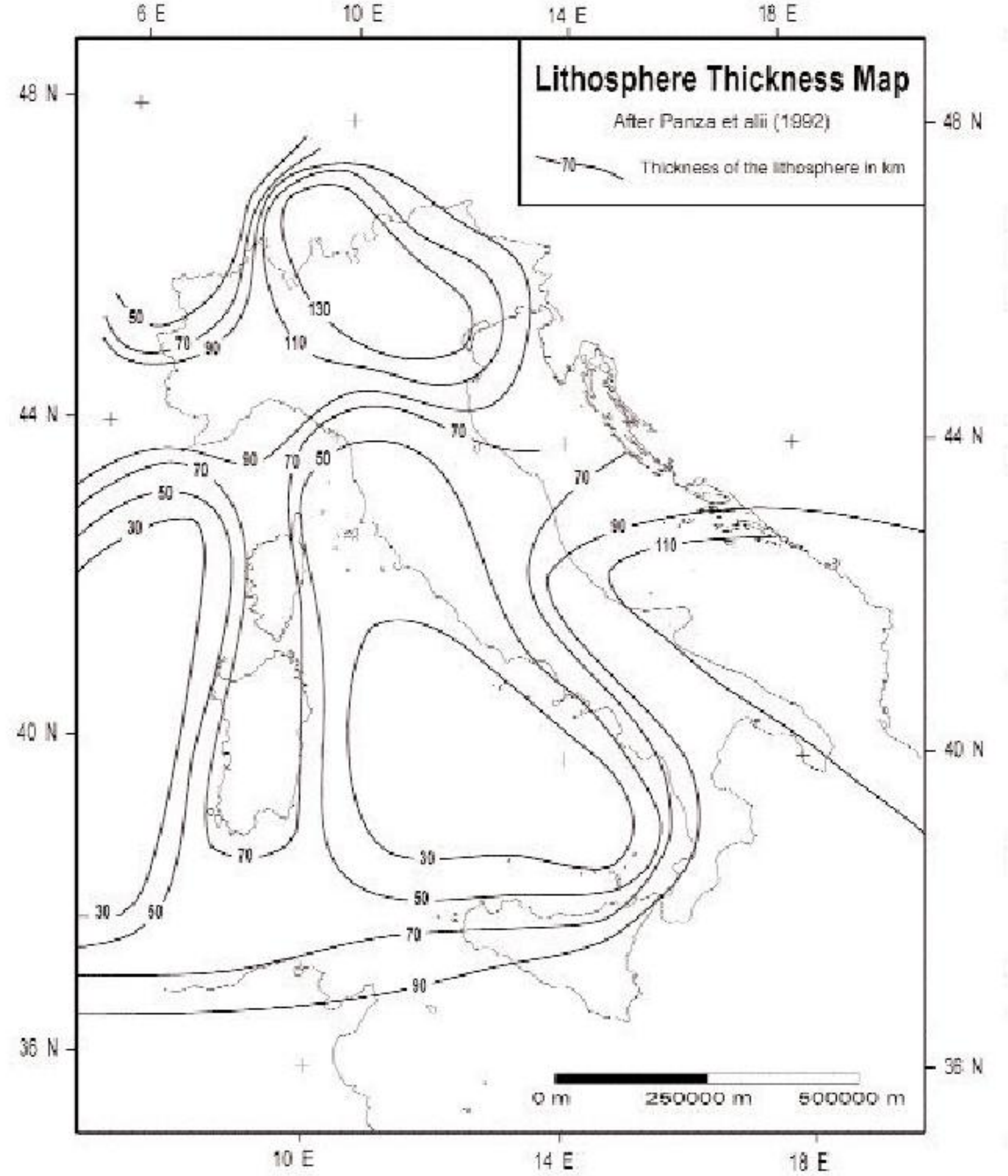


Fig.1.20- Lithosphere thickness map of the Tyrrhenian Sea and sourrounding areas (from PANZA *et alii*, 1992).

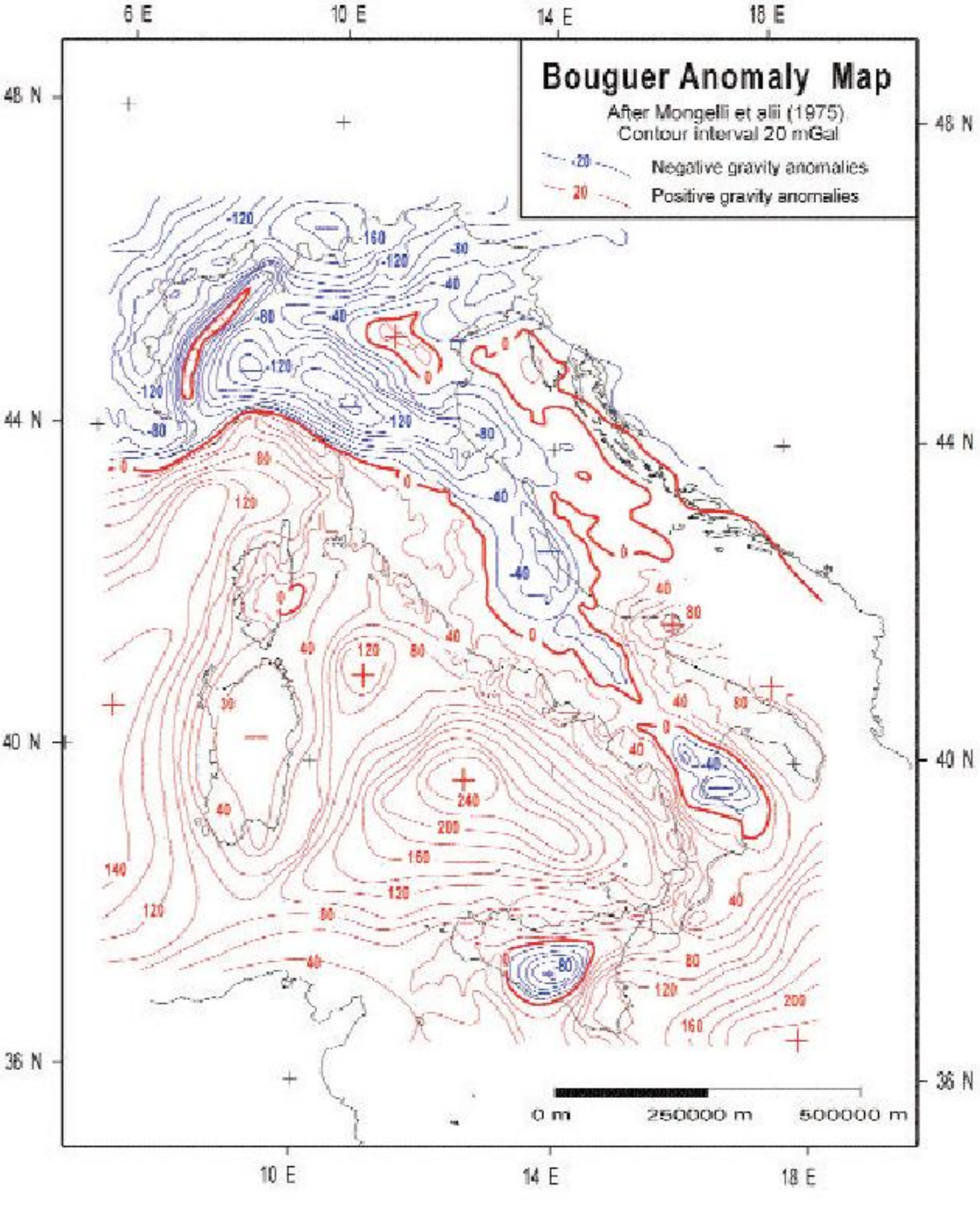


Fig.1.21- Bouguer anomaly map of the Tyrrhenian Sea and sourrounding areas (from MONGELLI *et alii*, 1975).

Sardinia-Corsica block has roughly normal thickness of the crust but thinned lithosphere. Thus, the uplift that characterized the Sardinia-Corsica block can be related to the thermal erosion of the lithosphere. Based on the apatite fission-track analysis in northern Corsica, CAVAZZA *et alii* (2001) show that the uplift of 2 km that affected together Sardinia and

Corsica with the Alpine Corsica started in the Late Early Miocene. It appears to be a uniform upward movement related to isostatic rebound. An explanation of this phenomenon can be related to the opening of the Provencal basin to the west. The mantle upraised along the rift zones, determining partial melting and a residual lighter mantle, has lower density of 20-60 kg/m^3 than the undepleted mantle. The residual mantle, less dense, when displaced to the east,

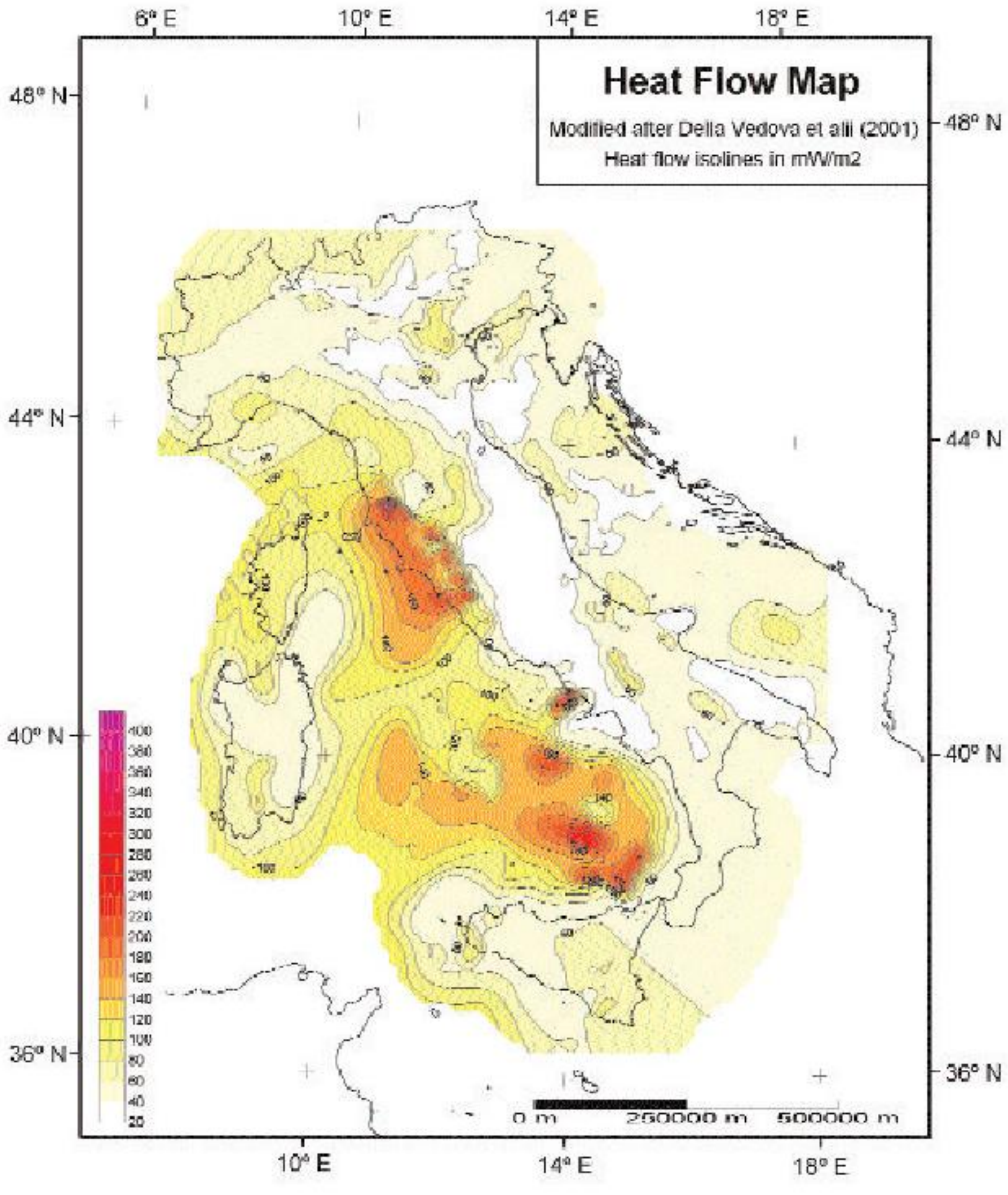


Fig.1.22- Heat flow map of the Tyrrhenian Sea and sourrounding areas. Modified in SCROCCA *et alii* (2008) from MONGELLI *et alii* (1991); CATALDIN *et alii* (1995); DELLA VEDOVA *et alii* (2001).

should generate a mass deficit with respect to the western limb of the ridge, where this low density mantle did not propagate. Thus, the generalized uplift of the Sardinia-Corsica block can be explained with the movement eastward, beneath the Sardinia-Corsica continental crust, of the depleted lighter mantle (DOGLIONI *et alii*, 2004).

The uplift can be also related to the thinning of the mantle lithosphere connected with process of intensive convective heating (thermal thinning).

Authors	Crust thickness	Lithosphere thickness	Method
MORELLI *et alii*, 1967; 1976	20-30 km	-	Seismic surveys
EGGER *et alii*, 1988	33-34 km	-	Seismic refraction surveys
PANZA *et alii*, 1992	-	70 km	Waves surface dispersion analysis
SCARASCIA *et alii*, 1994	25-35 km	65-80 km	Wide-angle seismic profiles
GVIRTZMAN & NUR, 2001	30 km	100 km	Crustal vs mantle contribution to topography
YEGOROVA & STAROSTENKO, 2002	24-28 km	80 km	3D gravity modelling
SCROCCA *et alii*, 2003	30 km	-	Seismic surveys
FINETTI, 2005	35 km	-	Seismic transcrustal sections
PANZA *et alii*, 2007a; PANZA & RAYKOVA, 2008	20 km in the western side but increases eastward	40 km (west) - 70 km (east)	cellular velocity model derived from nonlinear tomographic inversion combined with the distribution vs depth of hypocentres
PANZA *et alii*, 2007b	30 km	70 km	Shear wave tomography

Tab.1- Methods used by several Authors to achieve data on the crustal and lithospheric thickness.

2 METHODOLOGIES AND DATA

2.1 Workflow

To achieve the aim prefixed and described in the previous chapter, several data available and methodologies have been used. The workflow of the aim achievement can be summarized as follows (Fig.2.1): focusing of the problem, that is, to better understand the Plio-Pleistocene evolution of Sardinia, study the main structure related to the tectonic affecting the Island at that times: the Campidano graben. Thus, has been made a bibliographic research on the knowledge concerning the recent evolution of the Sardinia, the structural setting of the Campidano graben, the geodynamic setting and the data that can be useful to study the trough, among which well-logs and seismic lines. The data acquired have been then arranged in a data-base to be revaluated and validated data and previous interpretation. After that, completed the well-logs and seismic interpretation, aimed mainly to the recognition of the structures affected the Samassi formation and the Plio-Pleistocene basalt lava flows, the two-way time structural map of the bottom of the Samassi formation, marker of the Plio-Pleistocene deformation, has been carried out. Using the fault lines interpreted in the seismic lines and the two-way time structural map the fault and Samassi formation surface respectively have been built. The 3D model has been used to realize several cross-sections perpendicular to the main structures and to calculate the extension that affected the base of the Samassi formation. The 3D surface has been restored to achieve the slip movement along the fault planes. Then the paleostress acting in the Campidano graben during Plio-Pleistocene times has been calculated. Finally, the data obtained concerning the Sardinian crust have been compared with the data regarding mainly the opening of the Tyrrhenian basin.

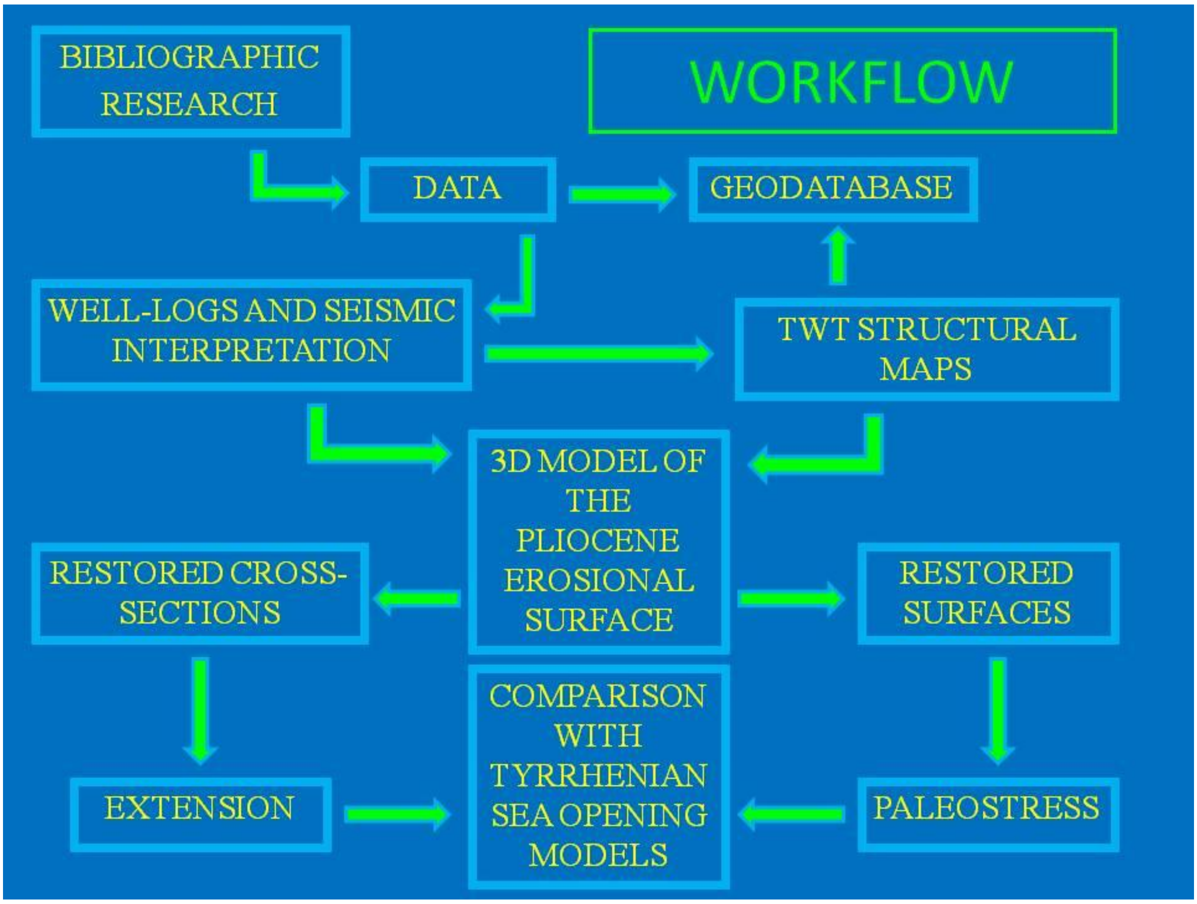


Fig.2.1- Workflow scheme.

2.2 Geodatabase

The geodatabase has been built in Monte Mario Italy 1 coordinate system using the software ArcGIS . It contains geological and geophysical maps, stored as raster files, that have been found and georeferenced, the seismic line traces, stored as linear shape files and the location of the deep wells, hydrogeological boreholes and common mid points or shot points of the seismic lines stored as punctual shape files (Fig.2.2). The geodatabase allows to compare simultaneously different kinds of data based on the geographic position, making easier the analysis. Furthermore, the geodatabase was continuously updating during the research, thus now contains, for example, also some results of the research as the two-way time structural map of the bottom of the Samassi formation.

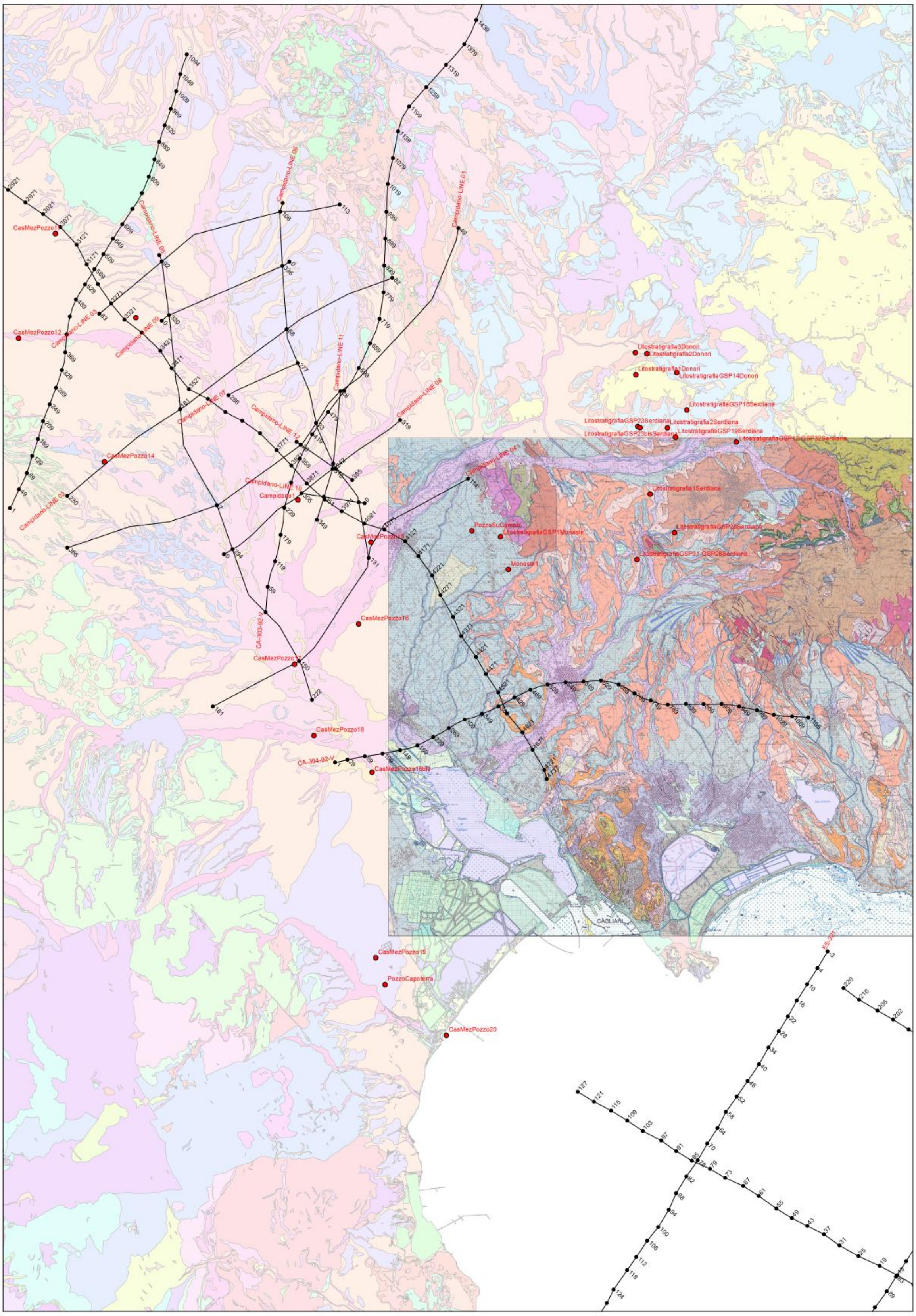


Fig.2.2- Example of layout view of the geodatabase. The raster geological map ("Foglio 557 Cagliari) is overlaid by the 50% transparent vectorial geological map (www.sardegnageoportale.it). The seismic lines with their common mid points and the boreholes are also shown.

2.3 Well-logs

The subsurface stratigraphy of the Campidano plain was investigated by three wells (Oristano1, Oristano2 and Campidano1) drilled by SAIS (Società per Azioni Idrocarburi in Sardegna; 70% Wintershall and 30% Regione Autonoma della Sardegna) in the first sixties, while the stratigraphy off-shore in the Cagliari Gulf was investigated by the Marcella well drilled in 1974 by AGIP (Tab.2.1). It has been possible downloaded the well profiles from the website of the ViDEPI (Visibilità Dati Esplorazione Petrolifera in Italia) Project (http://unmig.sviluppoeconomico.gov.it/videpi/). The lithological profiles of the three wells drilled by SAIS was compiled later by AGIP from oral information and documents of SAIS, thus, can not be extremely reliable. However, electric logs in the four wells (spontaneous potential and resistivity) are available and completely suitable for the interpretation. The spontaneous potential log is a measurement of the natural potential differences between an electrode in the borehole and a reference electrode at the surface, no artificial currents are applied. They originate from the electrical disequilibrium created by connecting formations vertically (in electrical sense) when in nature they are isolated. The principal uses of the spontanous potential log are to calculate formation-water resistivity and to indicate permeability. It can also be used to estimate shale volume, to indicate facies and, in some cases, for correlation. The resistivity log is a measurement of a resistivity of a formation, that is its resistance to the passage of an electric current. It is measured by resistivity tools. Conductivity tools measure the conductivity of a formation or its ability to conduct an electric current. It is measured by induction tools. Conductivity is generally converted directly and plotted as resistivity on log plots. Most rock materials are essentialy insulator, while their enclosed fluid are conductors. Hydrocarbons are the exceptions to fluid conductivity and, on the contrary, they are infinitely resistive. When a formation is porous and contains salty water the overall resistivity will be low. When this same formation contains hydrocarbons, its resistivity will be very high. Resistivity profiles give also lithological informations. In most sand-shale sequences, shale tend to have a moderate constant value and the sandstones generally lower values. Other rocks as limestones, salt or coal have high resistivity values.

Because the stratigraphic studies of this wells were carried out at the end of the sixties, during this work they have been reinterpreted taking into account the new and more precise and detailed magneto-bio-chronostratigraphic schemes and the improvements of the knowledge of the stratigraphy in the sourrounding areas of the Campidano derived from the new field surveys realized for the CARG Project.

WELL	SURVEY	YEAR	COORDINATES	DEPTH
ORISTANO1	SAIS	1964	lat. 30°49'40"; long. 3°52'30"	1,802 m
ORISTANO2	SAIS	1964	lat. 39°59'20"; long. 3°55'10"	1,700 m
CAMPIDANO1	SAIS	1964	lat. 39°22'25"; long. 3°30'00"	1,700 m
MARCELLA	AGIP	1970	lat. 38°55'46"58; long. 9°05'16"67	2,456 m

Tab.2.1- Wells drilled for hydrocarbon research in Sardinia. The coordinates are expressed with Monte Mario longitude for the on-shore wells (SAIS) and Greenwich longitude for the off-shore well (MARCELLA).

2.4 Seismic lines

The seismic lines interpreted during this research were acquired in the first sixties by SAIS, in the early seventies by AGIP and in the first nineties by the joint-venture AGIP-Progemisa S.p.A. (Tab.2.2).

SURVEY	YEAR	km	AREAS
SAIS	1960-1961	344 km	Northern Campidano
SAIS	1960-1961	137 km	Southern Campidano
AGIP	1970	147 km	Cagliari Gulf
AGIP-PROGEMISA	1991-1992	285 km	Campidano

Tab.2.2- Seismic lines acquired in the Campidano graben and used for this research.

SAIS acquired 32 seismic lines in the Campidano of Oristano (344 km), with an irregular grid, and 12 seismic lines in the southern Campidano (137 km), forming a rather vast grid. In 1988, Total Mineraria, in cooperation with IFP (Institut Français du Pétrole), digitized and reprocessed the seismic lines acquired in the southern Campidano. During two-year period 1990-1991 Progemisa S.p.A., in collaboration with ENSPM (École Nationale Supérieure du Pétrole et des Moteurs) and IFP, reprocessed the seismic lines acquired in the northern Campidano (Fig.2.4).

In 1970, AGIP acquired 6 seismic lines (147 km) in the off-shore continuation of the Campidano graben (Cagliari Gulf) with a regular grid (Fig.2.4).

In 1991-1992, the joint-venture AGIP-Progemisa S.p.A. acquired further 8 seismic lines (285 km) both in the northern and southern Campidano plain (Fig.2.4).

The recording parametres and the processing sequences for the different acquisition are shown in Tab.2.3.

SURVEY	RECORDING PARAMETRES	PROCESSING SEQUENCE
SAIS (northern Campidano)	Energy source: dynamite Shot interval: 360 m Charge size: 10-15 kg Charge depth: 12-16 m Cable: split-spread Number of groups: 24 Group interval: 30 m Geophones per group: 6 Near trace offset: 15 m Far trace offset: 345 m Instruments: analogue Record length: 5.0 s Low cut filter: 22/32 Hz High cut filter: 63 Hz	Record length: 4.0 s Sample interval: 4 ms Initial processing Common Mid Point gather Statics correction Amplitude modulation Time invariant band pass Pre-deconvolution mute Deconvolution CMP residual static correction Normal moveout correction Mute CMP stack Statics correction Localised XF domain deconvolution Time variant bandpass filtering Time variant scaling
SAIS (southern Campidano)	Energy source: dynamite Shot interval: 30 m Source array: single hole Charge: 10 kg Source depth: 16 m Cable: split-spread Number of groups: 24 Group interval: 30 m Geophones per group: 6 Near trace offset: 15 m Far trace offset: 345 m Instruments: analogue Sample interval 4 ms Record length: 5.0 s Low cut filter: 22 Hz High cut filter: 63 Hz	Record length: 3.5 s Sample interval: 4 ms Initial processing Common Mid Point gather Scaling Static correction Pre-deconvolution filter Deconvolution Dynamic correction Front end mute CMP stack Static correction Time variant bandpass filtering Time variant scaling Adaptive F-K filtering
AGIP (Cagliari Gulf)	Energy source: aquapulse Filter: 10-80 Hz Cable: 1600 m Geophones: 32 Array: 650 ft Amplifier: binary gain Charge size: 4 guns pop	Edit Deconvolved before stack Normal Move Out Stack 1200% T.V. filter Playback (unfiltered)
AGIP-PROGEMISA	Energy source: vibroseis Number of vibrators: 4 Vibrators spacing: 12 m Sweep number: 15 or 20 Pattern length: 36 or 72 m V.P. interval: 40 m Sweep tipe: linear and random Sweep length: 16 s Start frequency: 7 or 8 Hz End frequency: 70 Hz Geophones per group: 24	Processed length: 6 s Reformating SegD Instrument phase compensation Minimum phase compensation Resampling 2 ms to 4 ms Geometry updating-edition Slalom CMP gathering Geom. spreading compensation Static corrections Time variant prefilter Predictive deconvolution

	Number of groups: 120 Distance between groups: 40 m Sample rate: 2 ms Record length: 6 s Low cut filter: 4 Hz High cut filter: 87.5 Hz	Preliminary velocity analysis Normal Move Out Muting Long Trace Simulation Static correction Automatic medium wavelength Final velocity analysis NMO corrections Automatic short wavelength Equalization L1000 Stack 6000% fold coverage Phase Lag +90 deg. Zero phase shaping Time variant filter Trace equalization Migration in time Coherency enhancement Trace equalization Analogic display

Tab.2.3- Recording parametres and processing sequences of the different seismic lines acquisition.

The seismic lines acquired by SAIS and AGIP-Progemisa S.p.A. have been available for this research by Regione Autonoma della Sardegna (RAS) and Progemisa S.p.A. The seismic lines, both stacks and migrates, have been then scanned to achieve raster files. Instead, the off-shore seismic lines acquired by AGIP have been downloaded by the website of the ViDEPI Project. First of all, the graphic aspect of the scanned seismic lines have been optimised using Adobe Photoshop and Corel Draw softwares (Fig.2.3). After that, the seismic lines have been put all in the same horizontal (1:25.000) and vertical (1 sec = 5 cm) scale.

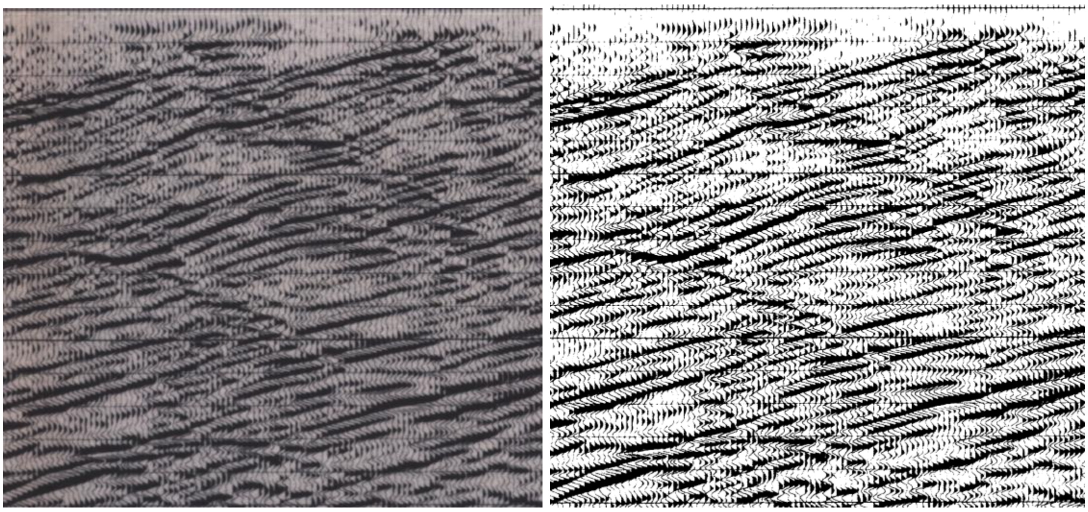


Fig.2.3- Example of optimized raster file (right image) from the original scanned seismic line (left image).

Operation on the datum plane were not necessary because in all the seismic lines it refers to the mean sea level. Afterwards the optimized seismic lines have been printed and re-scanned to achieve lighter raster files maintaining anyway a good quality image. To project the surface geology on the seismic profiles, as location map of the wells and seismic lines has been used the vectorial geological map edited in 1:25.000 scale for the PPR (Piano Paesaggistico Regionale) of the Regione Autonoma della Sardegna (www.sardegnageoportale.it). The seismic interpretation started with the calibration of the lines projecting the wells parallel to the strike of the main structures in the area. Once that the main reflectors were pinpointed,

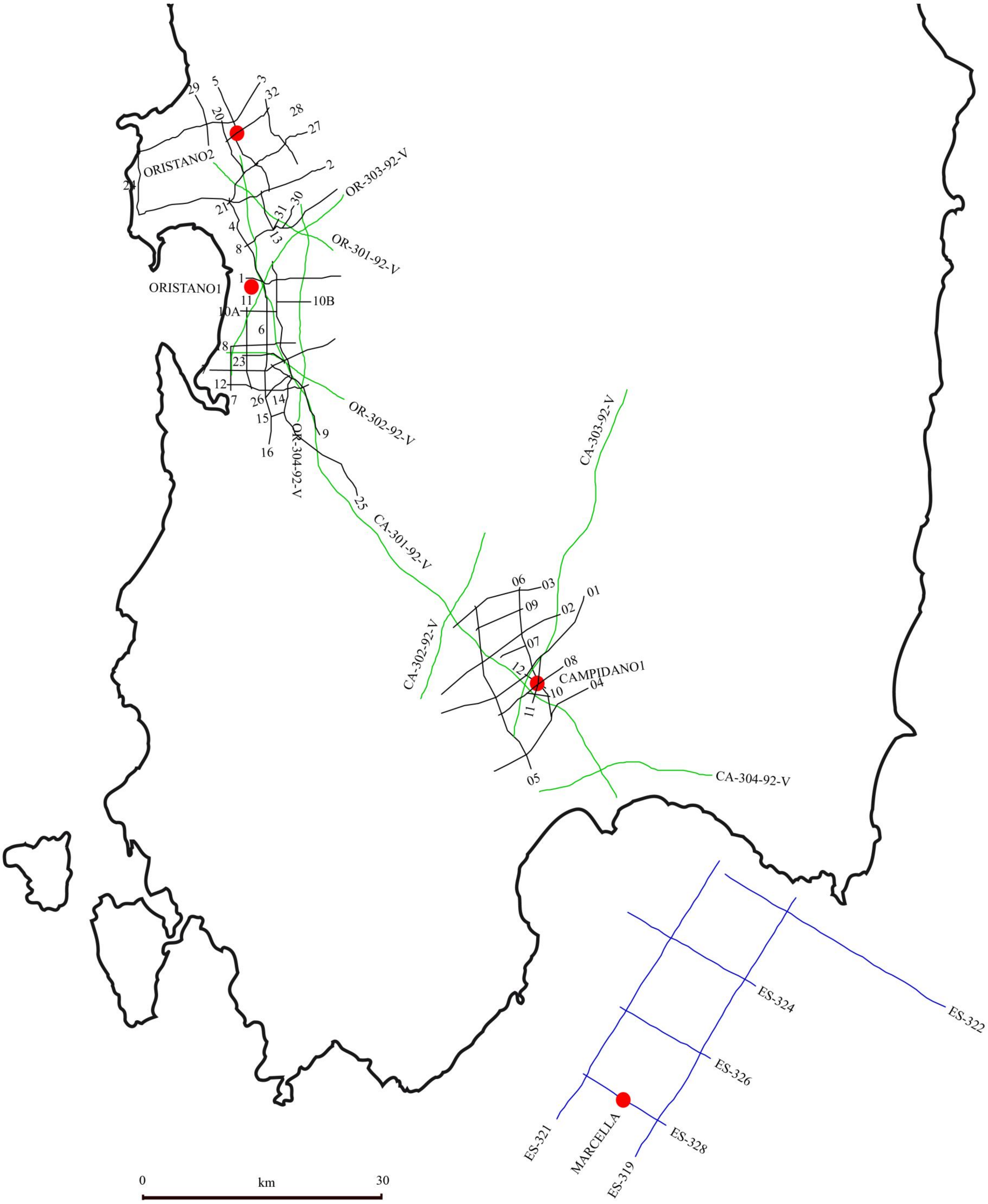


Fig.2.4- Location map of the seismic lines and wells used for this research. Black lines: SAIS; Blue lines: AGIP; Green lines: AGIP-Progemisa.

they have been picked in all the lines, checked by loop and identifying the structures that affected them.

2.5 3D Modelling and validation

To investigate the deformation during Pliocene and Pleistocene times, it has to be identify the faults that affected the formations that constrain this periods. Thus, the deformation affecting the erosional surface at the bottom of the Samassi formation, and its recognition, was the main focus of the seismic interpretation. Then the two-way time structural map of the bottom of the Samassi formation has been carried out by hand and digitized using ArcGIS and, after that, the shape file achieved has been imported into MOVE, software of the Midland Valley (Academic Licence) (Fig.2.5).

MOVE allows to assign each iso-line its vertical time value, placing them in the 3D space, and interpolating them the 3D surface can be built. To build the 3D surface starting from the two-way time structural map, though realized with interpretive method, is already a type of validation of the seismic interpretation made with the simple interpolation of the seismic horizons picked in the seismic lines. On the other hand, to build the faults surfaces the fault lines detected in each seismic lines were interpolated. The fault surfaces created have to honouring also the cut-off lines of the two-way time structural map. Finally, the 3D model of the Plio-Pleistocene erosional surface, together with the faults that affected it, has been created.

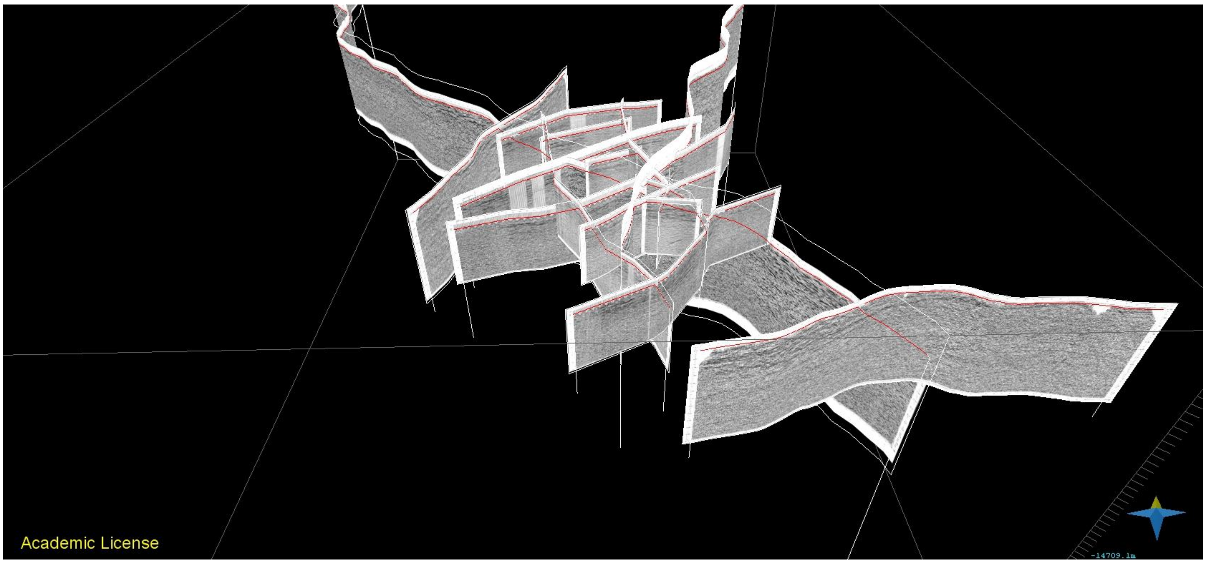


Fig.2.5- Seismic lines of the southern Campidano georeferenced in 3D space in MOVE.

2.6 Extension values and paleostress

The built 3D model has been used to calculate the extension values and the paleostress.

Concerning the extension that affected the Campidano graben in Plio-Pleistocene times, several cross-sections, perpendicular to the main structures inerpreted, have been achieved by the 3D model. These cross-sections were restored using the line-length balancing method, achieving the extension values. It was chosen, to calculate the extension values, to use cross-section carried out from the 3D model and not directly the seismic sections because these last are not straight and perpendicular to the main structures. Thus, the extension values achieved from the cross-sections, are more reliable than those that would have been achieved by restoring of the seismic lines.

To obtain the paleostress active in Plio-Pleistocene times, instead, the 3D surfaces were restored using the method from ROUBY *et alii* (2000), that allows the restoration of complex fault patterns and obtain the direction of slip on faults and then using the Geomechanical Modelling module of MOVE software. By closing the gaps between the hangingwall and footwall cut-off lines of the surface was possible to recognize the movement vectors of the rejoined points from the hangingwall to footwall cut-off lines. These vectors, projected on the fault plane surfaces, give the fault slip orientations. The plunges and trends of the "slickensides" were achieved using a stereoplot by the intersection of the fault plane and the vertical plane that contain the horizontal component of the total displacement vector. After that, it was possible calculate the paleostress using the right dihedra and fault slip data inversion methods (ANGELIER & MECHLER, 1977).

This method to achieve the slip orientations of the faults it was necessary to compensate for the absence of reliable Plio-Pleistocene faults with visible slickensides.

The comparison of the two methods allows a validation of the results.

3 RESULTS

3.1WELL-LOGS INTERPRETATION

The study of the subsurface geology in the Campidano area started with the interpretation of the available profiles of wells Oristano1, Oristano2, Campidano1 and Marcella, that is the preliminary work to calibrate the seismic lines. The detailed studies of the biostratigraphic profiles (PECORINI & POMESANO CHERCHI, 1969; TILIA ZUCCARI, 1969; POMESANO CHERCHI, 1970; PALA *et alii*, 1982; CHERCHI & MURRU, 1985) of the wells, together with the electric logs, allowed a critical review of the stratigraphy of the wells determined in the studies cited above where the stratigraphic interpretation took into account bio-chronostratigraphic schemes that were obviously less detailed and updated than those available now. Furthermore, the stratigraphic interpretation edited in the well profiles of the Campidano1, Oristano1 and Oristano2 can not be considered reliable because were compiled later by AGIP by oral informations and documents of the SAIS and show differences with the stratigraphic interpretation proposed by the Author cited above. A new stratigraphic interpretation is then proposed considering the updated magneto-bio-chronostratigraphic schemes (CASCELLA *et alii*, 1998).

For the sake of semplicity, the depositional sequences recognised in the wells and described below will be named with abbreviations that refer to the ages of the sequences. These abbreviations are the same for every well: PQ: Plio-Quaternary; LP: Lower Pliocene; UM: Upper Miocene; LMM: Lower-Middle Miocene.

The correlation between the wells is shown in Fig.3.1.5.

3.1.1 Marcella well

The Marcella well (Fig.3.1.1), drilled in the off-shore of Cagliari, is the first well that has been interpreted, because is the most recent drilled and the information in the profile, compiled directly by AGIP (MONTIS & MATTEI, 1974) are more reliable than those in the profiles of the wells drilled on-shore.

From the spontaneous potential and resistivity logs three main different depositional sequences have been detected: the upper sequence (PQ) is recorder between the sea bottom to 350 m; the middle sequence (UM) between 350 m and 600 m; the lower sequence (LMM) between 600 m to 1,785 m. All the depth are referred to the rotary table, that is 16.45 m above the sea level. The recording of the electric logs started at 154.5 m, thus, no information are available for the sedimentary succession between the sea bottom at 79.45 m and 154.5 m.

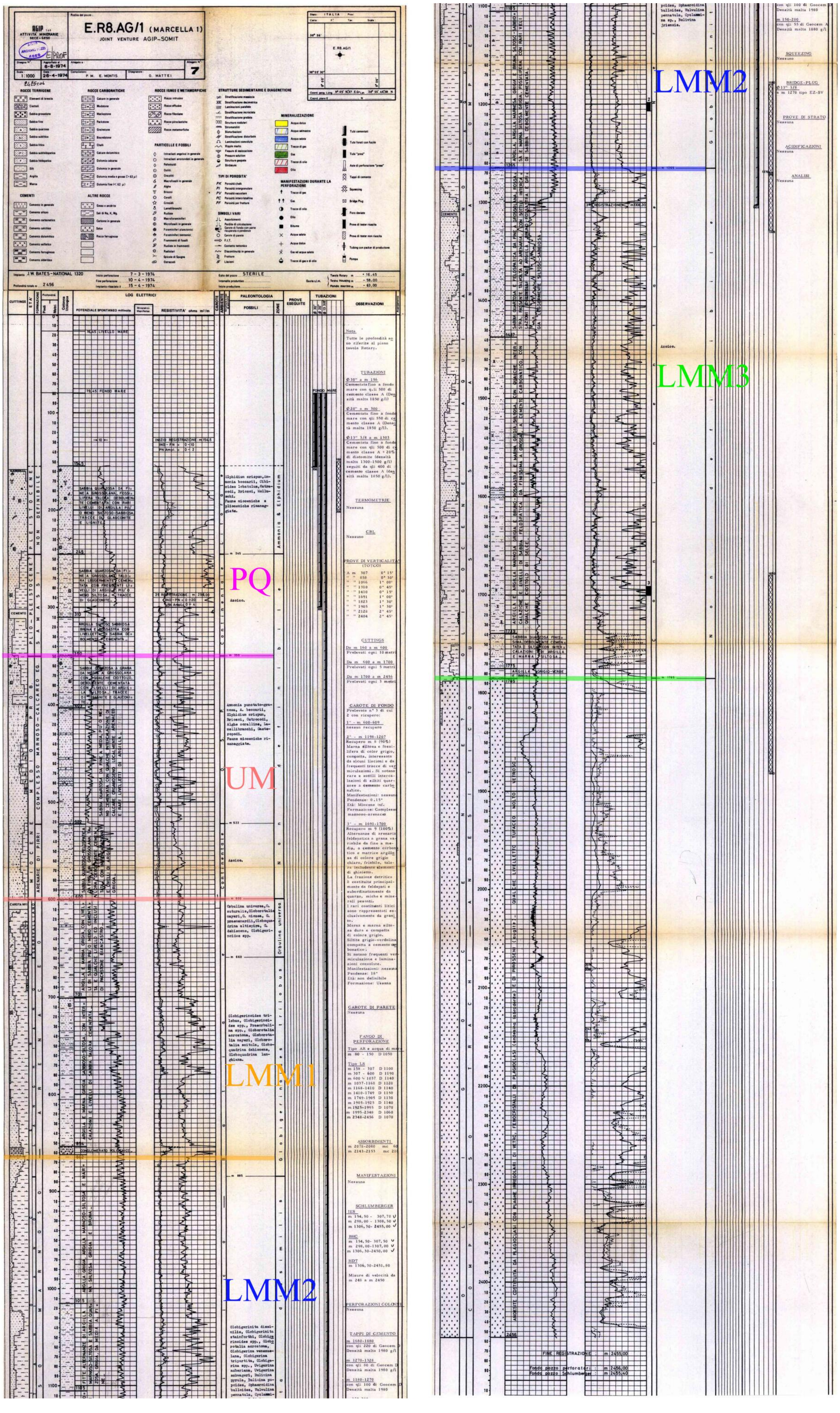


Fig.3.1.1- Marcella well profile (http://unmig.sviluppoeconomico.gov.it/videpi/) showing the depositional sequences recognised: PQ: Plio-Quaternary; UM: Upper Miocene; LMM: Lower-Middle Miocene.

The lower limit of the upper depositional sequence (PQ) is an unconformity marked in the log by a shifting of the spontaneous potential base-line. The shift of the spontaneous potential base-line that occurs at 300 m is not due to lithological causes but to the change in the pipe diameter and the starting of the second recording step. This sequence is composed by the Plio-Quaternary succession, characterized in the upper part (154.5 to 245 m) by fine to coarse quartz sand with intercalated rare clay levels. The occurrence of glauconite in this sequence is indicative of continental shelf marine depositional environments. This interval is referred to Pleistocene time considering the occurrence of *Elphidium crispum* and *Ammonia beccarii* together with reworked Pliocene and Miocene faunas (MONTIS & MATTEI, 1974). The middle part (245 m to 310 m) is composed by fine to coarse quartz sand with much silty-clay levels intercalated. The occurrence of glauconite and the absence of fossils can be indicative of continental depositional environments. The lower part (310 to 350 m) is made up of silty-sandy clays with sand levels intercalated. This interval is also azoic, showing furthermore reddish colours of the clays that confirms the continental depositional environment for this interval too. Thus, the lower and middle part of this sequence can be correlated with the Samassi formation (PECORINI & POMESANO CHERCHI, 1969), considering the depositional environment and the age of the underlying sediments and the Pleistocene sediments of the upper part of this sequence.

The lower limit of the middle depositional sequence (UM) occurs at 600 m, again marked by an unconformity highlighted in the log by a shifting of the spontaneous potential base-line, and consists of three parts. The upper part (350 m to 403 m) of the sequence is composed by quartz sand with intercalated clay levels and glauconite traces. In the middle part (403 m to 522 m), the sequence is similar but is characterized by finer sand and rare levels of organogenic limestons and clays. The organogenic limestones are highlighted by positive peaks in the resistivity log. The lower part (522 m to 600 m) of this sequence is characterized by more coarse sand with intercalated levels of grey clays. The fossils found, mainly reworked miocene faunas, do not help to define the age of this sequence, but the stratigraphic position and the lithological description allow to ascribed the lower part of the sequence to the Pirri Sandstones (PECORINI & POMESANO CHERCHI, 1969), Serravalian in age, and the middle and upper part to the *Pietra Cantone "Auct."* and *Tramezzario "Auct."*, Tortonian in age, of Cagliari Limestones (GANDOLFI & PORCU, 1967; CHERCHI, 1974), of which the *Pietra Forte "Auct."*, the uppermost part, has not crossed by the well. It is not possible to know if this part of the Cagliari Limestones occurs in the subsurface because the maximum thickness detected in outcrop (60 m) is almost below the seismic resolution.

The lower depositional sequence (LMM) starts at 1785 m, and this boundary is not marked by a clear changes in the curves of both electric logs, even though it is a contact between sedimentary and magmatic rocks. This sequence has been divided into three parts: from 600 m to 862 m (LMM1), from 862 m to 1265 m (LMM2), from 1265 m to 1785 m (LMM3).

The upper part (600 m to 701 m) of the LMM1 is characterized by grey clays and marls, with intercalated sand levels and rare organogenic limestones. The faunas found, indicating the *Orbulina universa* zone, together with the lithological information, allows to ascribe this succession to the Fangario clays (CHERCHI, 1974), referred to a Upper Langhian-Lower Serravalian age. The underlying part (701 m to 862 m) is composed by grey sandy-silty clays and marls with intercalated sandy levels. The bottom of this succession is characterized by 8 m of polygenic conglomerate. The occurrence in the faunas of *Globigerinoides trilobus* and *Praeorbulina glomerosa* (MONTIS & MATTEI, 1974) allows to refer this succession to the Upper Burdigalian-Langhian. Thus, this succession can be correlated with the Gesturi marls (CHERCHI, 1974). Also the conglomerate at the base confirms that the correlation can be proper. In fact, in outcrop too, the base of Gesturi marls are sometimes marked by a conglomerate layer. Furthermore, the positive peaks in the resistivity log can be correlated with the epiclastite layers in the Gesturi marls that crop out in the hills to the east of Cagliari and referred to the Langhian. Underlying the conglomerate (LMM2), a succession (862 m to 1015 m) composed by grey clays, marly-silty clays and grey and brown silty marls occurs. This succession lies above 90 m (1015 m to 1105 m) of slightly more coarse sediments, characterized by alternated marly-silty clay and fine to medium quartz sand layers. Below it (1105 m to 1265 m), again a succession composed by grey and brown sandy-marly-silty clay and grey silty marl, fossiliferous, with alternated rare sand layers occurs. The fossils found between 862 m and 1265 m, allow to refer this succession to the *Globigerinita dissimilis* zone (MONTIS & MATTEI, 1974). Thus, it can be correlated with the Marmilla Formation (CHERCHI, 1985), but a correlation with the Arenarie di Serralonga member of the Nurallao Formation (FUNEDDA *et alii*, 2012) for the lower part can be supposed. The lowermost part (LMM3) (1265 m to 1785 m) of the lower depositional sequence (LMM) is azoic and is composed between 1265 m and 1437 m by fine to coarse quartz and feldspathic reddish sand with intercalated thin layers of brown-reddish and grey sandy-silty clays. From 1437 m to 1739 m grey and brown-reddish marly clays and silty marls with intercalated very fine to coarse feldspathic sand layers and rare flint pebbles occur. The bottom of this succession is characterized, between 1739 m and 1775 m, by very fine quartz sand with intercalated silty clays and marls, and, between 1775 m and 1785 m, by grey-green and brown clays. This succession depicts a continental depositional environment that can be correlated with the Ussana Formation (PECORINI & POMESANO CHERCHI, 1969). The meaning of this continental succession, in terms of basin evolution, is the same of the Ussana Formation, that is, continental deposits between the overlying marine deposits of the Nurallao and/or Marmilla Formations and the underlying pre-Miocene basement, in the well represented by the Oligo-Miocene volcanic complex as well as onshore. In fact, under the lower depositional sequence (LMM), the well crossed up to the bottom of the well 1785 m to 2456 m) andesites with labradorite and augite with intercalated some tuffaceous layers. These andesite are likely the same that crop out in the Sarroch and Pula areas, and that have been called Andesiti di Monte Arrubiu of the Sarroch volcanic complex (BARCA *et alii*, 2009).

3.1.2 Campidano1 well

The Campidano1 well (Fig.3.1.2) shows a stratigraphic succession similar to that of the Marcella well. In fact, the spontaneous potential and resistivity logs allow to discern the same three main depositional sequences: the lower boundary of the upper depositional sequence (PQ) is recorded at 502 m; the middle depositional sequence (UM) is recorded between 502 m and 682 m; the lower depositional sequence (LMM) between 682 m and 1162 m. All the depth are referred to the rotary table, that is 26.45 m above the sea level. The recording of the electric logs started at 200 m.

The lower limit of the upper sequence has been detected from the resistivity log and the cores informations above and below this boundary. No evidences of it occur in the spontaneous potential log. In the well profile, the lithological description of the recovered cores 4 (444 m to 449 m) and 5 (534 m and 539 m) differ because the first contains reworked fossils of Upper Miocene and Lower Pliocene, the second only Miocene fossils. At 502 m, the resistivity log shows a peak that can be interpreted as an unconformity. This sequence is composed by alluvial gravel in the uppermost part (0 m to 40 m) and a pebbly-silty-marly complex between 40 m and 502 m (Samassi formation, PECORINI & POMESANO CHERCHI, 1969). Middle-Upper Pliocene-Quaternary age, considering the reworked *Globorotalia margaritae* (Zanclean) found, can be infer. The boundary between Pliocene and Pleistocene can be supposed at 325 m, where a peak in the resistivity log could mark it.

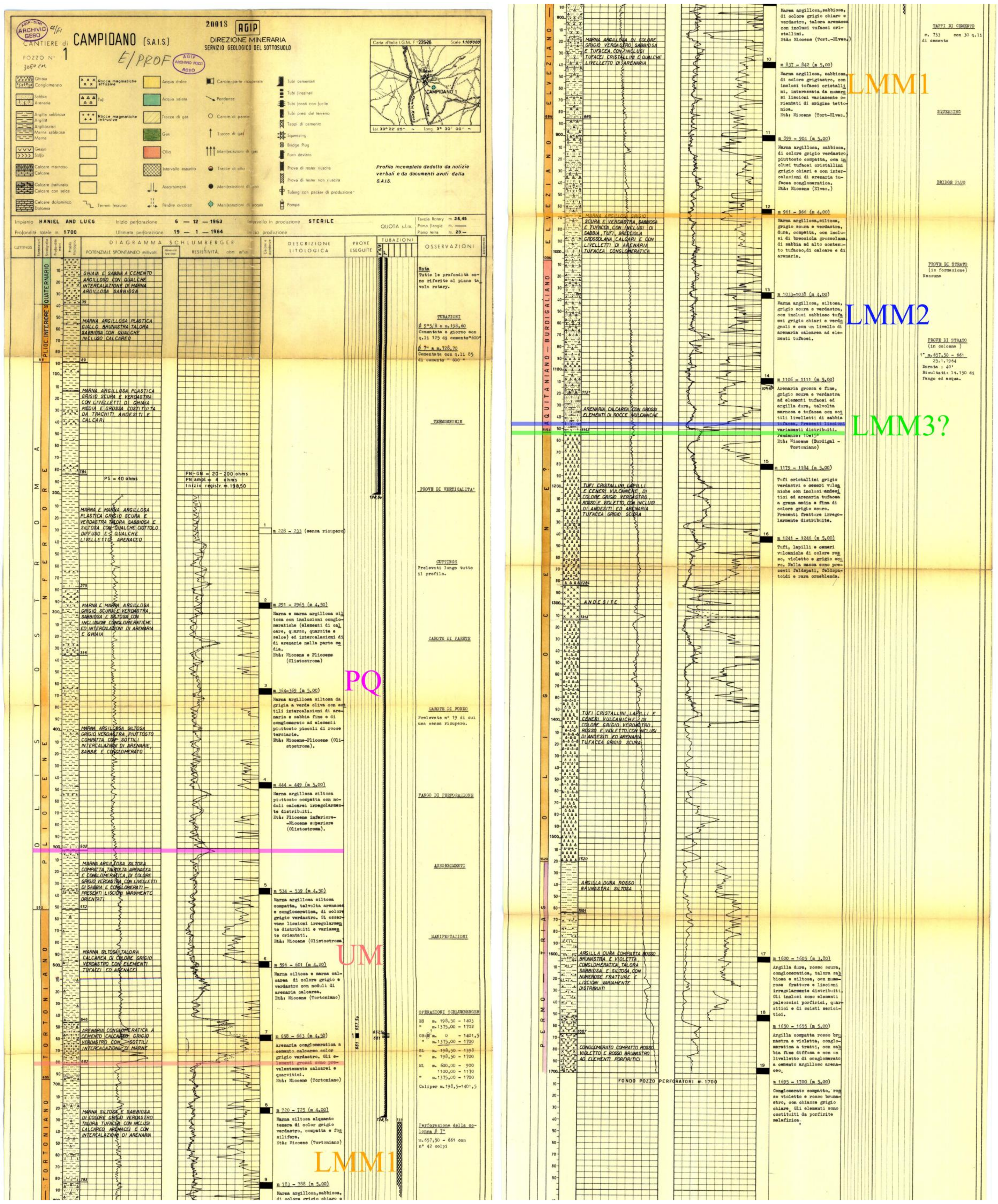


Fig.3.1.2- Campidano1 well profile (http://unmig.sviluppoeconomico.gov.it/videpi/) showing the depositional sequences recognised: PQ: Plio-Quaternary; UM: Upper Miocene; LMM: Lower-Middle Miocene.

At 682 m, it is clear in both the spontaneous potential and resistivity logs, the lower limit of the middle depositional sequence (UM). It is composed in the upper part (502 m to 646 m) by grey marls with intercalated silty layers, containing lamellibranchies, and in the lower part (646 m to 682 m) by conglomeratic sandstones with intercalated marly levels. The fossils allow to ascribe the upper part of this sequence to the *Globorotalia menardii* zone, and, therefore, to refer it to Tortonian age, allowing furthermore the correlation with the lower part of the Cagliari Limestones (GANDOLFI & PORCU, 1967; CHERCHI, 1974), *Pietra Cantone "Auct."*. The fossils recovered in the lower part, instead, are ascribable to the *Globorotalia miozea* sub-zone. The deducted Serravalian age and the lithology allow to correlate this sequence with the Pirri Sandstones (PECORINI & POMESANO CHERCHI, 1969).

As in the Marcella well, the lower depositional sequence (LMM) detected lies above the Oligo-Miocene volcanic succession. In the Campidano1 well this limit occurs at 1153 m. The LMM sequence has been divided into two parts: from 682 m to 966 m (LMM1), from 966 m to 1,153 m (LMM2). The upper part (682 m to 788 m) is composed by fossiliferous silty marls that are ascribable up to 725 m to the *Globorotalia miozea* subzone and between 725 m and 788 m to the *Orbulina suturalis* subzone. This succession can be correlated with the Fangario clays (CHERCHI, 1974), Middle Langhian-Lower Serravalian in age. Between 788 m and 966 m a monotonous succession of fossiliferous grey marls occurs, which can be divided into two part ascribable to two different subzones: *Praeorbulina glomerosa* (788 m to 899 m) and *Globigerinoides trilobus* (899 m to 966 m). Thus, this succession can be entirely correlated with the Gesturi marls (CHERCHI, 1974), Upper Burdigalian-Langhian in age. Furthermore, as in outcrop, a tuffaceous epiclastite layer, 12 m thick, occurs at 904 m, marked by a positive peak in the spontaneous potential log. Instead, the electric logs do not mark the transition to the underlaying succession, inasmuch the succession continues to be composed, up to the top of the Oligo-Miocene volcanic complex, by silty marls. Only the last 10 m are composed by conglomerates with andesitic pebbles. However, the *Globoquadrina dehiscens* and the *Globigerinita dissimilis* subzones allow to correlate this succession with the Marmilla Formation (CHERCHI, 1985), Aquitanian-Lower Burdigalian in age. The conglomerates could be correlated with the Ussana Formation (PECORINI & POMESANO CHERCHI, 1969) or the Duidduru Conglomerate Member of the Nurallao Formation (FUNEDDA *et alii*, 2012).

Between 1,162 m and 1,700 m, the Oligo-Miocene volcanic complex occurs, composed mainly by andesitic lavas, tuffs and breccias. Intercalated in the volcanic succession, between 1,520 m and 1,686 m, a violet-reddish clayey-sandy layer, sometimes conglomeratic, with andesitic and Paleozoic rock pebbles, occurs.

3.1.3 Oristano1 well

The Oristano1 well (Fig.3.1.3), compared with the two well profiles described above, shows a succession quite different in regard to the Plio-Quaternary evolution. The electric logs allow to detect four main depositional sequences: the lower boundary of the uppermost depositional sequence (PQ) is recorder at 740 m; the underlying depositional sequence (LP) is recorder between 740 m and 844 m; the middle depositional sequence (UM) is recorder between 844 m and 901 m; the drilling stopped at 1,802 m before reaching the base of the lower depositional sequence (LMM). All the depths are referred to the rotary table, that is 5.45 m above the sea level. The electric logs recording started at 200 m.

The upper part (0 m to 360 m) of the first sequence is composed by clayly-sandy-pebbly alluvial deposits. Between 7 m and 33 m two fossiliferous marine layers occur, likely attributable to the *"Panchina Tirreniana" "Auct."*, Tyrrhenian in age. Between 306 m and 322 m into the alluvial deposits, basalt lava flows are intercalated. These basalts have to be correlated, likely, with those of the Sinis and Capo Frasca peninsulas, where however no radiometric ages are available. An age interval between 3.8 Ma and 2.6 Ma (Piacenzian) can be supposed considering the ages of the Monte Arci basalts. Between 360 m and 640 m the succession is characterized by a silty-marly complex with conglomerates that contain pebbles of metamorphic rocks, granite, quartz, trachyte and marl, of continental depositional environment. The reworked faunas of Miocene and Lower Pliocene allow to assign a Upper Pliocene age to this succession and to correlate it to the Samassi formation (PECORINI & POMESANO CHERCHI, 1969). Again to the Samassi formation can be correlated the succession between 640 m and 740 m. In fact, the recovery of coastal-lagoon faunas as *Ammonia beccarii* and *Elphidium crispum*, perfectly preserved and therefore considered *in situ* (POMESANO CHERCHI, 1971), and the Miocene and Lower Pliocene reworked faunas allow to refer this succession to Middle Pliocene. The underlying sequence (LP) (740 m to 844 m) is composed by marine, fossiliferous, dark grey sandy marls. The *Globorotalia margaritae* found together to *Globorotalia puncticulata* allow to refer this succession to the

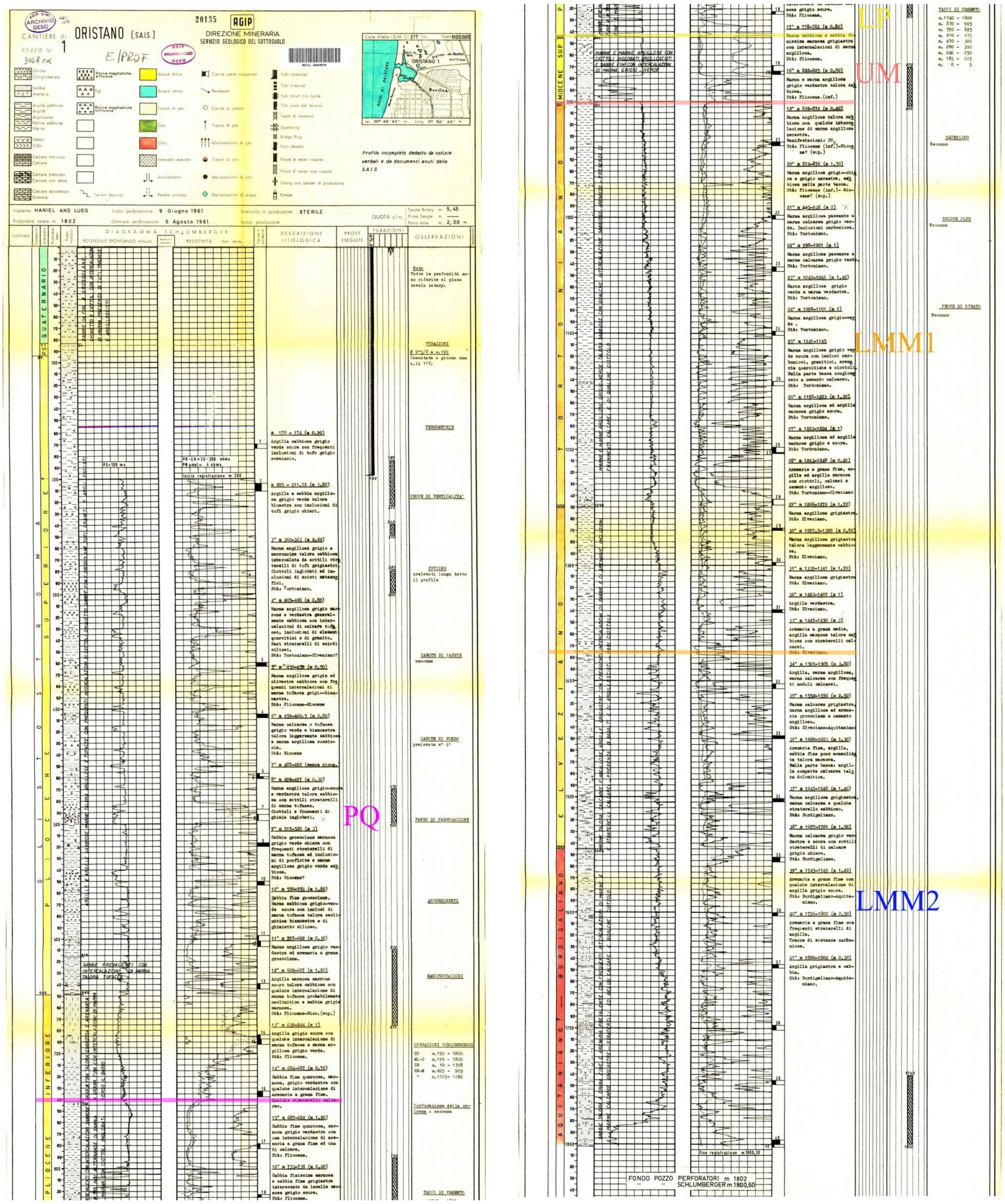


Fig.3.1.3- Oristano1 well profile (http://unmig.sviluppoeconomico.gov.it/videpi/) showing the depositional sequences recognised: PQ: Plio-Quaternary; LP: Lower Pliocene; UM: Upper Miocene; LMM: Lower-Middle Miocene.

Globorotalia margaritae/Globorotalia puncticulata concomitant zone (4.5-4.0 Ma) and to correlate it to the Nuraghe Baboe Formation (SPANO, 1989), Lower Pliocene (Zanclean) in age. The middle depositional sequence (UM) is between 844 m and 901 m and is the better marked in top and bottom by discontinuities in the electric logs. It is composed by sandy-pebbly sediments, with pebbles of metamorphic rocks, granite and quartz, with some intercalated marly-clayey layers. The *Globigerina eggeri multiloba*, *Globigerinoides obliquus extremus* and *Bulimina echinata*, allow to assign a Messinian age to this succession and to correlate it to the Capo San Marco Formation (PECORINI, 1972).

The lower sequence (LMM) (901 m to 1,802 m) is a monotonous succession of marls intercalated with fine sands and, in the lower part (from 1,403 m), with basic volcanic rock layers. It has been divided into two parts: from 901 m to 1,375 m (LMM1) and from 1,375 m to 1,802 m (LMM2).

It is possible to assign the succession from 901 m to 990 m to Tortonian age considering the *Globorotalia menardii* zone detected. The subzone *Globoquadrina altispira/Globorotalia miozea* allows to refer the succession between 960 m and 1,060 m to Serravalian age. The Langhian succession occurs from 1,060 m to 1,150 m, where the *Praeorbulina glomerosa* and *Orbulina suturalis* zones have been detected. The succession between 1,150 m and 1,375 m is Upper Burdigalian in age, because of the *Globigerinoides trilobus* zone. Thus, the Upper Burdigalian-Langhian succession can be correlated with the Gesturi marls (CHERCHI, 1974). Considering the age, the Serravalian-Tortonian succession can be correlated with the Fangario clays (CHERCHI, 1974) and Pirri sandstones (PECORINI & POMESANO CHERCHI, 1969), that, however, crop out roughly 100 km away, near Cagliari. The underlying succession (1,375 m to 1,650 m), ascribed to the *Globigerinita dissimilis* zone, allows to refer it to Aquitanian-Lower Burdigalian age and the *Globigerinoides primordius* subzone, detected in the lowermost part (1,650 m to 1,802 m) of this cycle, indicates Lower Aquitanian age. Thus, the Aquitanian-Lower Burdigalian succession can be easily correlated with the Marmilla Formation (CHERCHI, 1985).

3.1.4 Oristano2 well

The Oristano 2 well (Fig.3.1.4) did not cross the thick Miocene sedimentary succession drilled in the three wells previous described. The electric logs recording started at 200 m, and allow to detect three main depositional sequences: the lower limit of the upper sequence (PQ) is recorder at 650 m; the middle sequence (LP) is recorded between 650 m and 782 m; the lower sequence (UM) is recorder between 782 m and 842 m. All the depths are referred to the rotary table that is 5.45 m above the sea level.

The upper sequence (PQ) (0 m to 650 m) is composed by fluvio-lacustrine and lagoon-deltaic continental sediments. Between 218 m and 242 m a basalt lava flows occur. The second core (270 m to 275 m) is composed by alternated layers of sandy clay and coarse sand. The occurrence of *Globigerina pachyderma* allows to certainly refer this core to the Quaternary. The other cores of this cycle are mainly sterile but the stratigraphic position and the lithological characteristics allow to correlate the succession between 275 m and 650 m to the Samassi formation (PECORINI & POMESANO CHERCHI, 1969), and to suppose a Middle-Upper Pliocene age.

The middle sequence (LP) (650 m to 782 m) has been detected by the discontinuity in the resistivity log and, even though less clear, in the spontaneous potential log. This sequence is composed mainly by marine sandy clays of coastal depositional environment. The age of this succession can be referred to the Lower Pliocene considering the concomitant faunas, found in the core 8 (671 m to 676 m), that at the same time extinct (*Orthomorphina bassanii* and *Hopkinsina bononiensis*) and appear (*Discorbis bertheloti*, *Spiroloxostoma savenae*, *Globorotalia scitula sub-scitula* and *Bolivina apenninica*) in the Lower Pliocene. The core 9 (724 m to 729 m) is referred to Lower Pliocene too, considering the occurrence of *Bolivina leonardii* (Upper Miocene-Middle Pliocene) and the absence of typical Miocene faunas. The age assigned to the core 8 excludes Middle Pliocene age. Thus, this succession can be correlated to the Nuraghe Baboe Formation (SPANO, 1989).

The lower sequence (UM) (782 m to 842 m) is composed by coarse quartz sand and marly clay. Because of the absence of faunas, is not possible assign an age to this succession but, considering the stratigraphic position and the lithological features it can be correlate to the Capo San Marco Formation (PECORINI, 1972) of Messinian age.

Underlying the sedimentary succession, have been drilled mainly volcanic rocks. Between 842 m and 1,298 m are basaltic-andesitic lava flows that can be correlated to those that crop out to the north of the Oristano Campidano plain, of Burdigalian age. Between 1,298 m and 1,308 m a gravel layer with oysters occurs, of which is not possible hypothesize the age. The lower part (1,308 m to 1,700 m) is characterized by ignimbrites that can be correlated to those of the Monte Arcuentu volcanic complex, Upper Oligocene-Burdigalian in age.

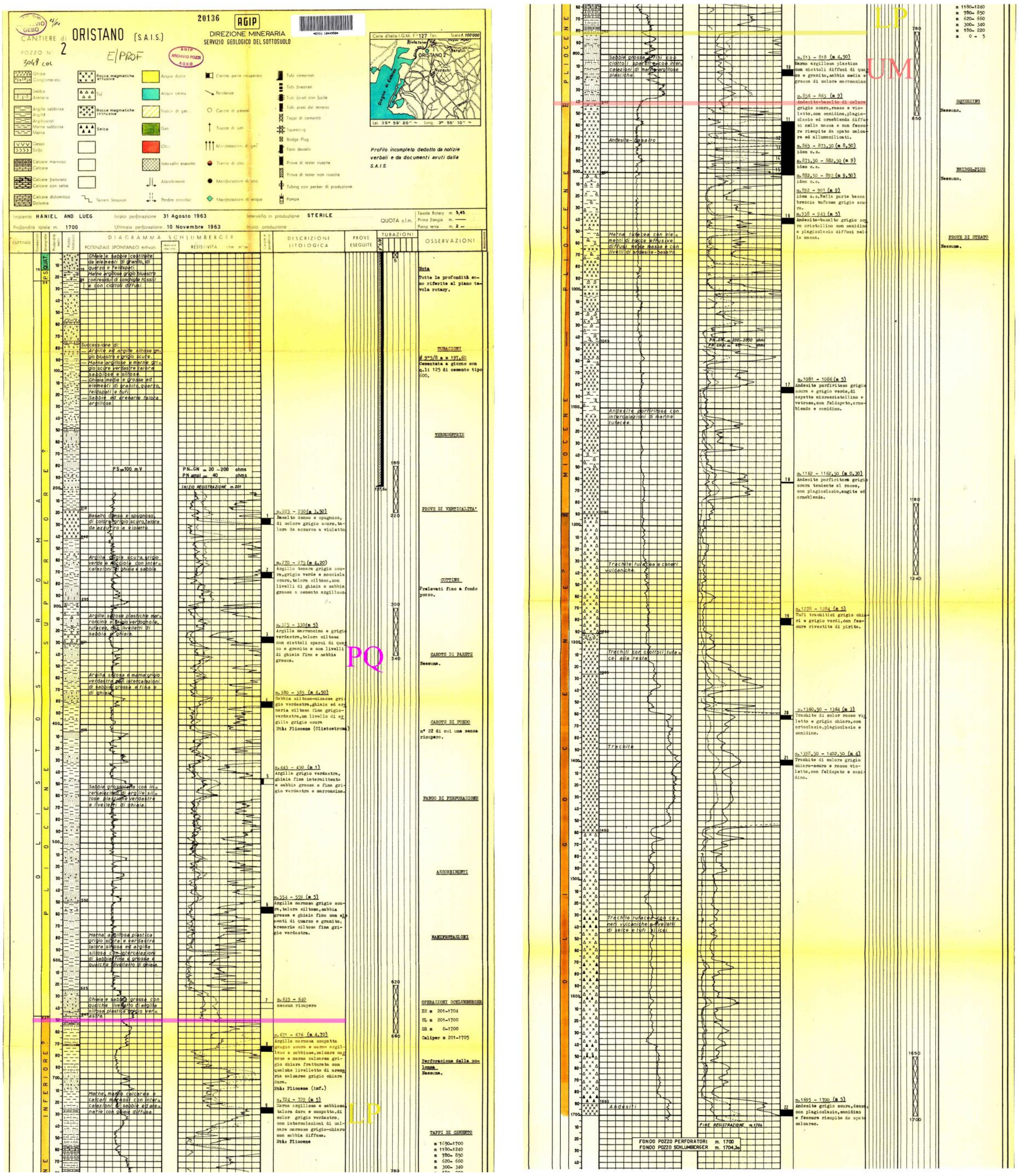


Fig.3.1.4- Oristano2 well profile (http://unmig.sviluppoeconomico.gov.it/videpi/) showing the depositional sequences recognised: PQ: Plio-Quaternary; LP: Lower Pliocene; UM: Upper Miocene.

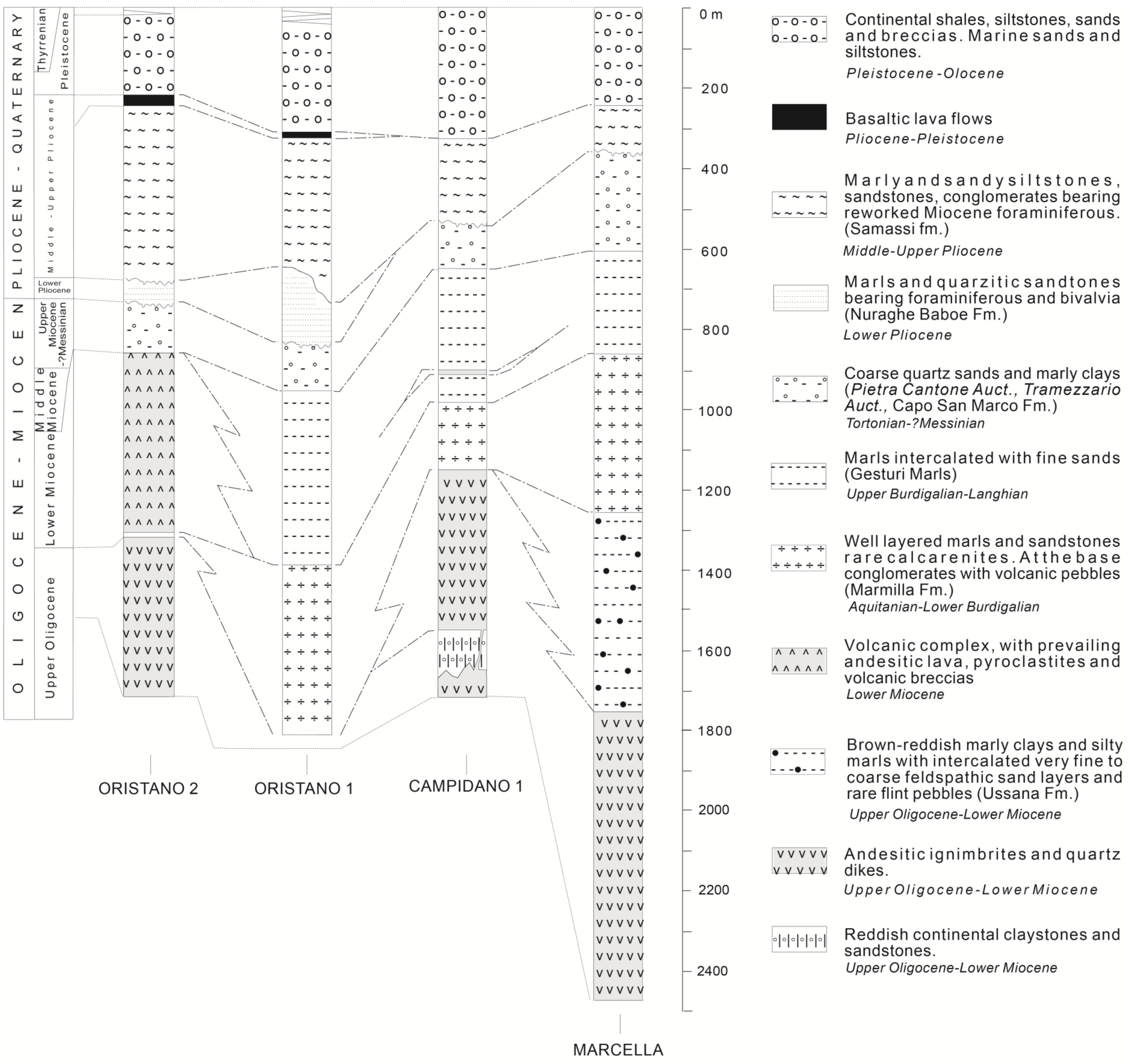


Fig.3.1.5- Schematic stratigraphy of the interpreted Mrcella, Campidano1, Oristano1 and Oristano2 wells

3.2 SEISMIC LINES INTERPRETATION

The interpretation of the seismic lines will be illustrated in this paragraph separated into three subsections depending on the geographical area: the off-shore of Cagliari, the southern Campidano and the northern Campidano.

The seismic lines interpretation started with the projection of the surface geology and structures on the seismic profiles, to have a control of the horizons and structures detected in subsurface. Whereupon, also the wells were projected on the closer seismic lines, proceeding along the main direction of the tectonic structures, to avoid to cross some structure between the well and the line.

The calibration of the seismic lines has been made using empirical velocity functions considering the more evident horizons in the seismic line and the main discontinuties detected in the wells between the depositional sequences, compatibly with seismic velocity and the seismic facies. Once that the seismic lines have been calibrated, the most important horizons detected have been picked and mapped in the other lines.

For the sake of semplicity, the same abbreviations used for the depositional sequences recognised in the wells have been assigned to the corresponding main seismic units recognised in the seismic lines: PQ: Plio-Quaternary; LP: Lower Pliocene; UM: Upper Miocene; LMM: Lower-Middle Miocene. The abbreviation A is used to indicate the acoustic basement.

3.2.1 Off-shore of Cagliari seismic lines

3.2.1.1 Seismic stratigraphy

The Marcella well has been used to calibrate the seismic lines in the off-shore of Cagliari. It lies above the ES-328 line (Fig.3.2.1), NW-SE oriented.

Five main reflector and six seismic units have been mapped in these lines, considering the depositional sequences detected in the Marcella well. The seismic units are described from the interface downwards.

The uppermost seismic unit (PQ) is characterized by the occurrence of clinoforms, mounds and parallel continuous even reflections towards the top. Towards the bottom parallel disrupted and chaotic reflections occur. This unit (PQ) reaches the main thickness (0.8 sec

TWT) in the line ES-321, between the shot points 136 and 112. The seismic facies interpretation allows to retain the upper part of this unit (PQ) of marine environment, consitued by the recent marine sediments, while the lower part of continental environment, and can be correlated to the Samassi formation. By correlation from Marcella well the age of this unit is Middle Pliocene-Recent. It is separated from the underlying units by an angular unconformity, that is often easy to recognised in all the lines because cuts across the faults and bedding planes of the sediments below it and. It lies above both the Upper Miocene and Middle Miocene successions.

The underlying seismic unit (UM) is characterized mainly by continuous subparallel reflections. The thickness of this seismic unit is 0.2 sec TWT. It can be mapped only in the ES-328 and ES-319 lines. In fact, in the ES-319 line, it is clearly cut by the Middle Pliocene erosional surface. A marine depositional environment can be inferred for this unit (UM). It is correlated to the Cagliari Limestones and the age is Upper Serravalian-Tortonian. It is separated from the underlying succession by an angular unconformity, even though sometimes a paraconformity can be detected.

The three underlying seismic units correspond to the three parts in which the depositional sequence LMM has been divided. Thus, these seismic units have been named downward LMM1, LMM2 and LMM3.

The LMM1seismic unit is characterized by continuous subparallel reflections and sometimes by transparent signals. The maximum thickness (0.6 sec TWT) is reached in the line ES-319 and it is possible to map in all the lines this unit. It is correlate to the Gesturi marls. The age is Upper Burdigalian-Langhian. An angular unconformity separates the LMM1 seismic unit from the underlying LMM2 seismic unit.

The LMM2 seismic unit is characterized by transparent signal and some parallel reflections. It reaches the maximum thickness (0.8 sec TWT) where the lines ES-326 and ES-319 intersect each other. This seismic unit (LMM2) is correlated to the Marmilla Formation, Aquitanian-Lower Burdigalian in age. It onlaps on both the underlying LMM3 seismic unit and acoustic basement.

The LMM3 seismic unit is characterized by chaotic and parallel disrupted reflections. This seismic unit can be mapped only in the line ES-328 and the maximum thickness (0.4 sec TWT) is reached between the shot points 25 and 37. The seismic facies allows to define a continental depositional environment for this seismic unit. It is correlated to the Ussana Formation, Upper Oligocene-Lower Miocene in age. It lies above the acoustic basement.

The seismic facies of the three seismic units just now described (LMM1, LMM2, LMM3) allow to confirm how shown from the interpretation of the electric logs of the LMM depositional sequence in the Marcella well. In fact, in the seismic lines, it is clear the transition from the continental depositional environment of the lowermost unit (LMM3) to the marine environment of the overlying unit (LMM2), where, in the top, the maximum flooding surface is shown. Upward, the seismic unit LMM1 constituting the regressive sedimentary sequence.

The acoustic basement (A) is mostly made up of the Oligo-Miocene magmatic products. Where these ones are missing, the occurrence of Paleozoic basement, that crop out extensively in the south Sardinia, can be supposed. Sometimes, this unit shows non-chaotic reflection that can be ascribed to the sedimentary volcanic succession related to the well know Oligo-Miocene magmatic activity.

3.2.1.2 Seismic structures

Only in two seismic lines acquired in the off-shore of Cagliari is possible to detect faults that affect the PQ seismic unit.

A fault has been detected in the ES-321 line (Fig.3.2.1), between the shot points 202 and 190. This fault dip to the east but it is not possible determine its strike because it is detected only in one seismic line. However, considering the dip of the fault line measured, about 65°, can be supposed that it is the true dip and, being the line NE-SW oriented, a NW-SE strike of the fault can be inferred. It can not be correlated with the on-shore western fault (Capoterra fault) that separates the Campidano plain from the Iglesiente-Arburese block because is located in the off-shore of Pula, to the west of the Gulf of Cagliari, where the continuation off-shore of the Capoterra fault should occur. From Middle Pliocene times, this fault has been had a throw of 700 m.

The other fault has been detected in the ES-322 line (Fig.3.2.1) between the shot points 16 and 34. As the previous fault described, this is detected only in this line, thus the strike direction of the fault plane is difficult to measure. In this case, however, the 40° dip angle measured can be an apparent dip of the fault, thus the fault plane can not be supposed perpendicular to the seismic line, NW-SE oriented. The fault, located in the southeasternmost part of the Cagliari Gulf, dips to the west and can have a NNW-SSE strike direction, parallel to the coastline in that area. If the supposed strike direction of this fault is correct, then it can

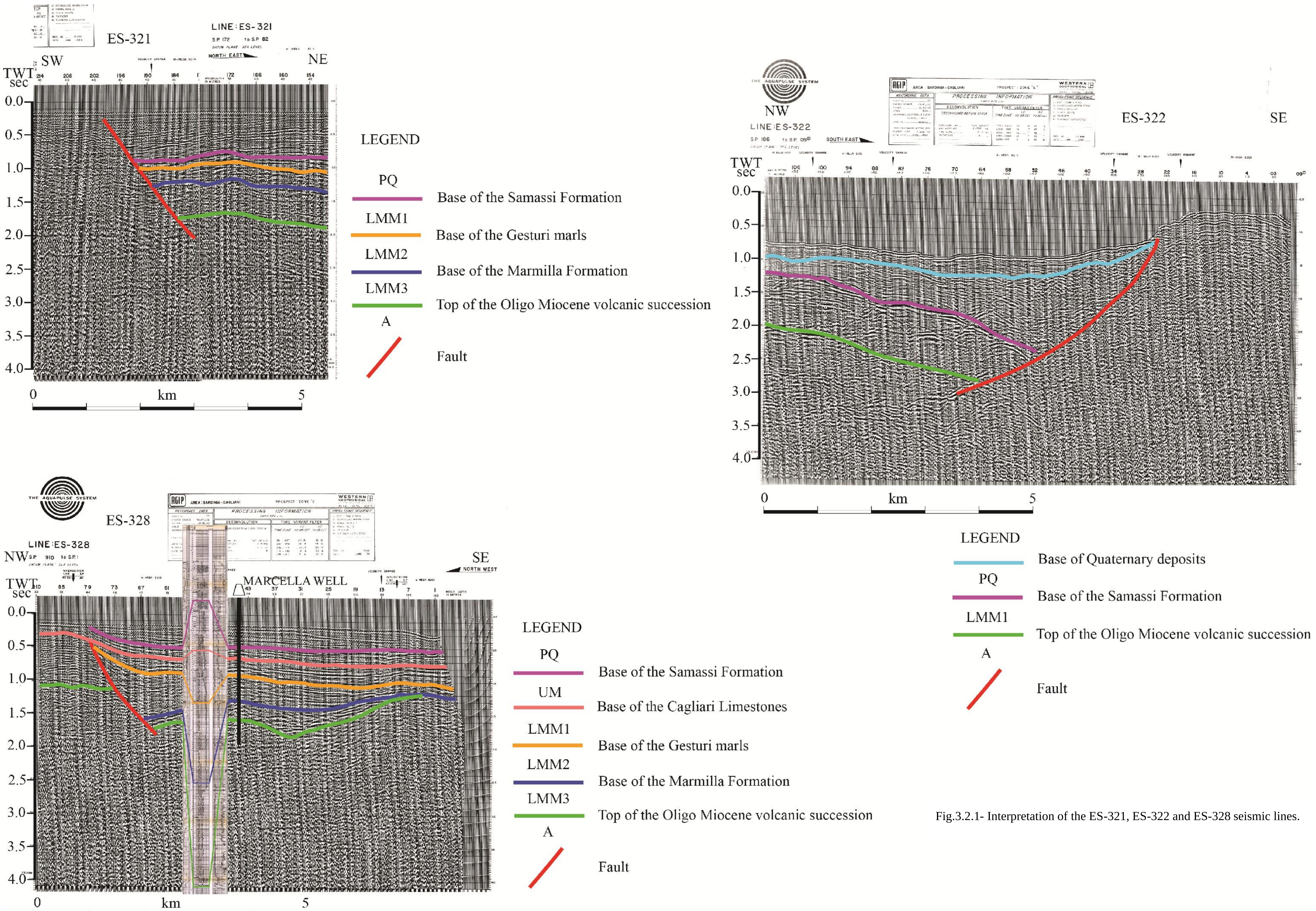


Fig.3.2.1- Interpretation of the ES-321, ES-322 and ES-328 seismic lines.

be correlated in the on-shore with the fault trending NNW-SSE between Capitana and Maracalagonis, east from Cagliari. The unconformity at the base of the PQ seismic unit is at -800 m below the sea bottom. The activity of this fault controlled the deposition of the lower part of the PQ seismic unit, that is those correlated to the Samassi formation, and seems to stop with the deposition of the upper part. In fact, only the lower part of the PQ seismic unit shows an increasing in thickness towards the fault.

Another fault has been detected between the shot points 73 and 85 in the ES-328 line (Fig.3.2.1). Also concerning this fault, the strike is difficult to measure. The dip angle, about 60°, suggests that can be the true angle and, if so, the fault dips to SE and strikes NE-SW, being the line oriented NW-SE. It controlled the deposition of the LMM2 seismic unit (Aquitanian-Lower Burdigalian succession). In fact, only the LMM2 seismic unit increase in thickness toward the fault. Furthermore, this fault seems to be sealed by the UM seismic unit.

3.2.2 Southern Campidano seismic lines

3.2.2.1 Seismic stratigraphy

All the onshore seismic lines acquired in the southern Campidano have been calibrated with the Campidano1 well, that lies on the line 08 (Fig.3.2.2) NE-SW oriented. Four main reflections and five seismic units have been mapped in the seismic lines.

The uppermost seismic unit (PQ), that coincides with the upper depositional sequence (PQ) detected in the Campidano 1 well, is characterized by subparallel disrupted reflections. The maximum thickness (0.9 sec TWT) is reached between the shot points 144 and 147 in the line 04. The seismic facies can be ascribed to continental depositional environment and correlate this seismic unit to the Samassi formation, Middle Pliocene-Quaternary in age. As in the seismic lines in the off-shore of Cagliari Gulf, it is separated from the underlying units by an angular unconformity, that can be mapped in all the lines.

The underlying seismic unit (UM) is characterized, in the line 08, at most by just three reflections, thus their seismic facies are undeterminate. From the Campidano1 well it is possible to estimate a thickness about 180 m, and considering the frequency (36 Hz) and the velocity of 2,7 km/sec a wavelenght of roughly 75 m, in agreement with the observed reflections, can be inferred. The UM seismic unit is attributed to the Cagliari limestones from well data and its age is Upper Serravalian-Tortonian. Furthermore, as in the off-shore lines, this unit is not continue, thus, can not be mapped in all the lines. An angular unconformity separes it from the underlying unit. Where it is missing, the Samassi formation lies directly above the deeper units.

The underlying seismic unit (LMM1) shows parallel continuous even and wavy reflections, sometimes transparent signals. It reaches its maximum thickness (0.6 sec TWT) between the shot points 220 and 260 in the line CA-304-92-V. The depositional environment is marine and it is correlate to the Gesturi marls, Upper Burdigalian-Langhian in age. As in the off-shore seismic lines, is possible to map it in all the lines but no evidences of angular unconformity that separates it from the underlying seismic unit (LMM2) occur.

The LMM2 seismic unit is characterized mainly by transparent signal, even though parallel disrupted reflections occur. The maximum thickness (0.8 sec TWT) is reached between the shot points 240 and 280 in the line CA-304-92-V. The depositional environment is marine and it is correlate to the Marmilla Formation. It onlaps on the acoustic basement (A).

The deeper seismic unit is the acoustic basement (A), constituted by the andesites of the Oligo-Miocene volcanic succession and, probably, by metamorphic basement. The Miocene marine succession onlapping on it.

3.2.2.2 Seismic structures

Concerning the structures that affected the uppermost seismic unit (PQ) in the southern Campidano seismic lines, unlike the off-shore ones, several normal faults have been detected. These faults are mainly clear in the NE-SW oriented seismic lines (lines 01, 02, 03, 04, 07, 08, 09, CA-302-92-V and CA-303-92-V), that is, perpendicular to the direction of the southern Campidano plain. Thus, the seismic lines that cross the Campidano plain from the western to the eastern edges generally show normal faults dipping to the east and to the west close to the western edge and the eastern edge respectively. In the central part of the trough, other normal faults occur too.

The fault in the western edge (Capoterra fault) can be recognize in the lines 04 (Fig.3.2.3) and CA-302-92-V. In the line 04 it occurs between the shot points 158 and 160. The dip angle is 70° towards the east. The fault had a minimum throw of 640 m during Plio-Quaternary times, considering the PQ seismic unit displaced, that are missing in the footwall. In the line CA-302-92-V the western edge fault occurs between the shot points 200 and 240. The dip angle is 45° towards the east, and can be supposed that is an apparent dip angle. The minimum throw in Plio-Quaternary times is 300 m, considering the displacement affecting the PQ seismic unit.

To the north, in the seismic lines 02, CA-301-92-V, 09 (Fig.3.2.2), 03 and CA-302-92-V is possible to recognize a normal fault that is in the center of the trough. This fault dips to the west of 65° and reaches the maximum throw (600 m) affecting the PQ seismic unit in the line 02, between the shot points 59 and 62.

Other faults in the center of the trough have been detected in the lines 01, 04 and 05.

In the central part of the line 01 (Fig.3.2.3), between the shot points 9 and 16, two normal faults occur: the westernmost one dipping to the east and the easternmost one to the west, causing a gentle anticlinal folding of the angular unconformity at the base of the PQ seismic unit and the underlying units. The throw of these faults are, for both, 100 m.

In the seismic line 04 between the shot points 134 and 136, a normal fault dipping to the east of 65° occurs, displacing the PQ seismic unit of 400 m.

In the line 05, oriented NNW-SSE, roughly parallel to the Campidano axis, two normal faults, with small throw (60 m and 100 m), affect the base of the PQ seismic unit.

The fault in the eastern edge can be recognize in the lines 01, 02, 04, 08 and CA-303-92-V.

In the line 01 the eastern wedge fault occur between the shot points 29 and 31. It dips to the west of 65°. To this fault is also related a gentle rollover anticline. Considering the top of the acoustic basement (A), the throw is roughly 700 m. In Plio-Quaternary times the minimum throw of 300 m is inferred by the displacement affecting the PQ seismic unit, that is missing in the footwall.

In the line 02 the eastern edge fault is recognized between the shot point 77 and 78. It dips to the west of 70°. Here, the rollover anticline is less clear that in the line 01. The minimum throw is 200 m considering the displacement affecting the PQ seismic unit.

In the line 04 the eastern edge fault is visible between the shot points 124 and 126. It dips to the west of 70°. In this line is not possible to recognized rollover anticline related to this fault. As in the seismic line 01, the throw is roughly 700 m considering the top of the acoustic basement (A). In Plio-Quaternary times the minimum throw of 440 m is inferred by the displacement affecting the PQ seismic unit, that is missing in the footwall.

The eastern edge fault is recognized in the line 08 between the shot points 312 and 316. It dips to the west of 65°. Also in this line the rollover anticline is shown. The throw considering the top of the acoustic basement (A) is roughly 500 m. In Plio-Quaternary times the minimum

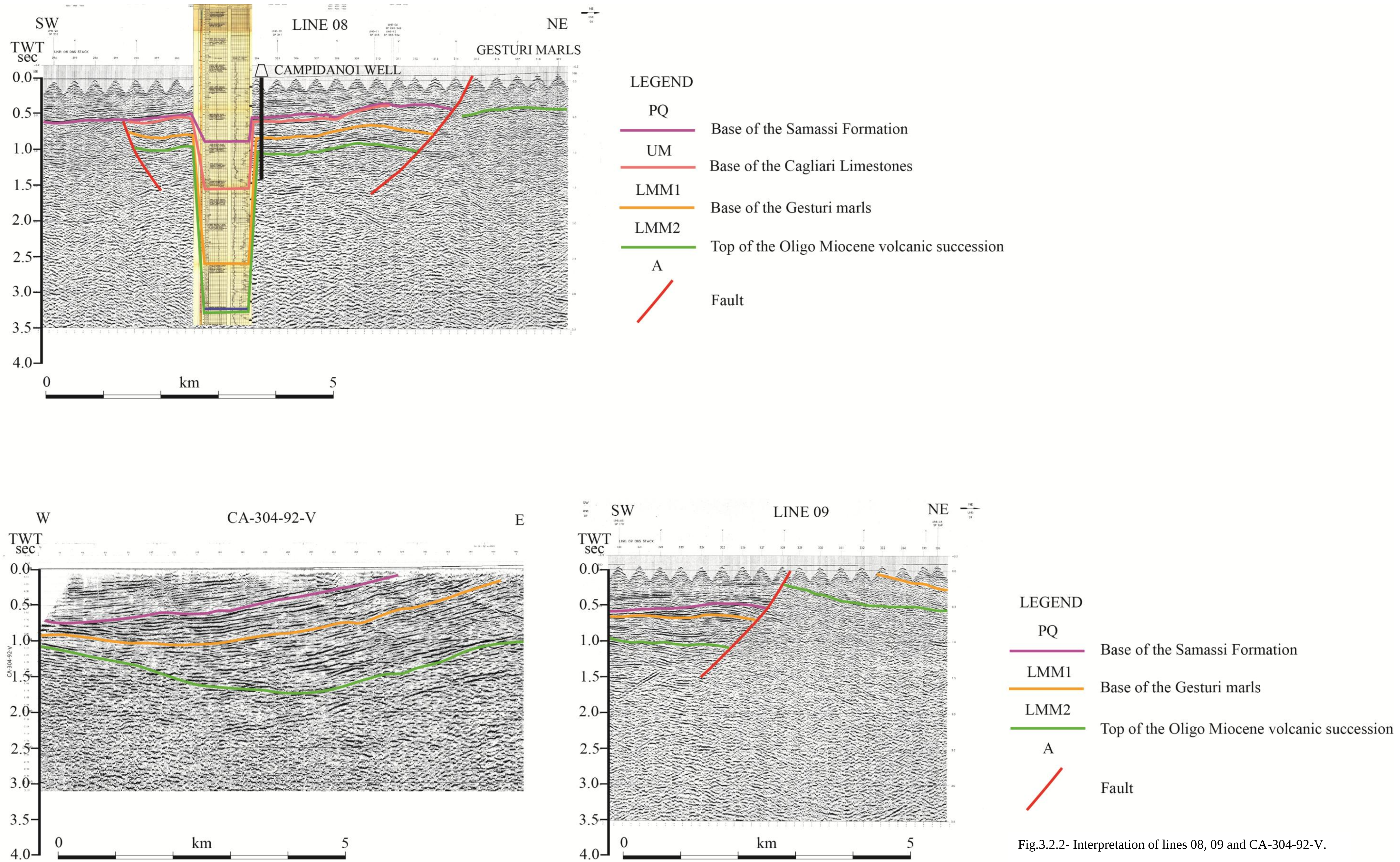


Fig.3.2.2- Interpretation of lines 08, 09 and CA-304-92-V.

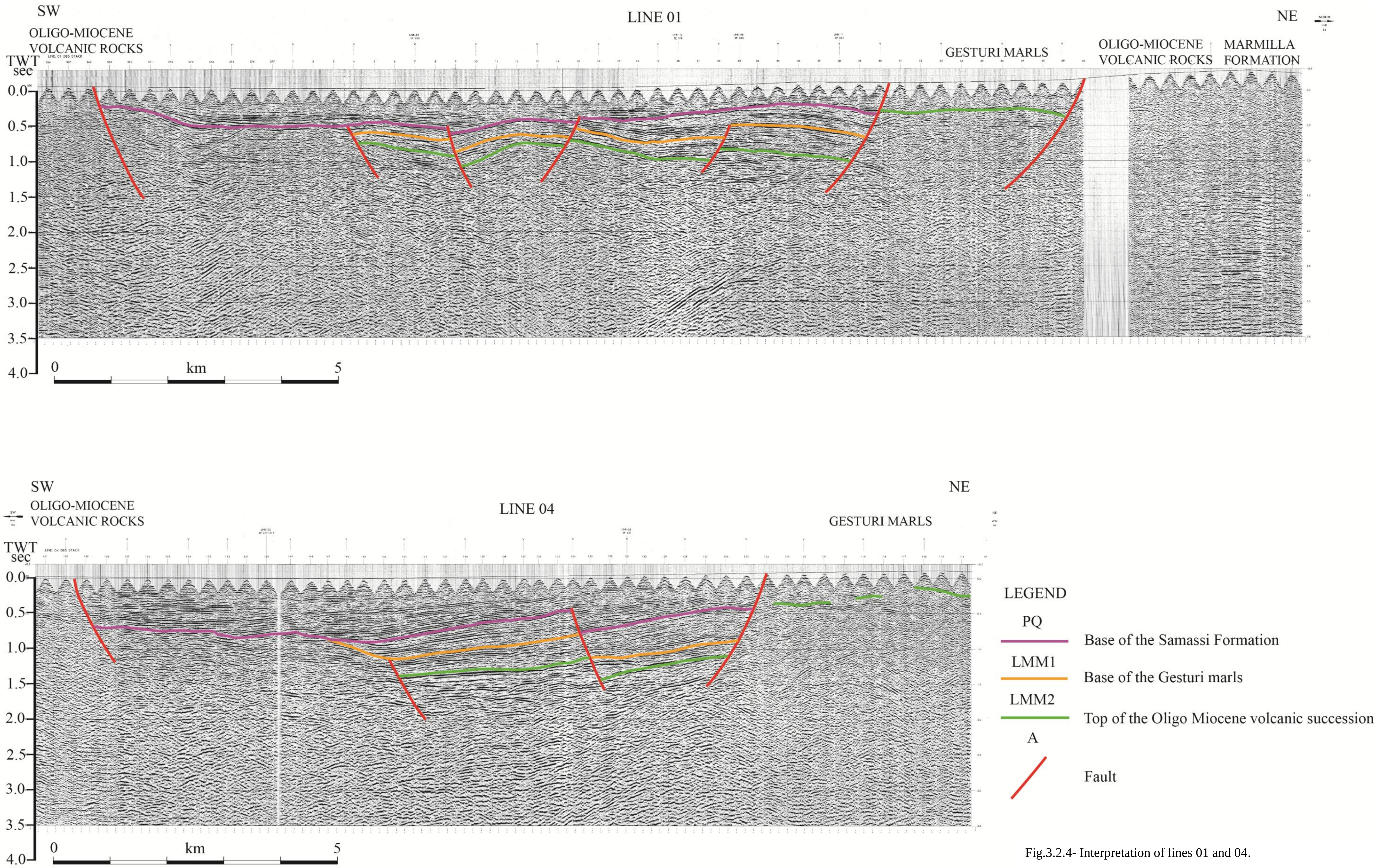


Fig.3.2.4- Interpretation of lines 01 and 04.

throw of 350 m is inferred by the displacement affecting the PQ seismic unit, that is missing in the footwall.

In the line CA-303-92-V the eastern edge fault is visible where this line intersects the line 01. Thus the fault shows in the line CA-303-92-V the same features that shows in the line 01.

Furthermore, the southernmost part of the eastern edge fault can be detected also in the line CA-301-92-V, between the shot points 4180 and 4500. Being this line almost parallel to the eastern edge, the fault result in the seismic line as a almost horizontal wavy line depending on the changes in direction of the seismic line and fault plane.

Two normal faults have been recognized in the lines 01 that were surely not active during Plio-Quaternary times.

The first fault, between the shot points 2 and 5, dips to the east of 65°. It is sealed by the PQ seismic unit. The minimum throw is 200 m considering the top of the acoustic basement (A), that is missing in the footwall.

The second fault, between the shot points 22 and 24, dips to the west of 60°. It affected the base of the LMM1 seismic unit and does not affect the overlying PQ unit. Thus this fault was not active from the Langhian. The throw considering the base of the LMM1 seismic unit is 100m.

Another fault that was surely not active in Plio-Quaternary times has been recognized in the line 04, between the shot points 143 and 145. It dips to the east of 60°. The minimum throw considering the top of the acoustic basement (A) is 200 m. This fault is sealed by the LMM1 seismic unit, thus was active at most until the Middle Burdigalian.

Even though the seismic signal is poor, a fault has been detected between the shot points 39 and 40 in the line 01. It dips to the west of 65°. In outcrop this fault has the Gesturi marls in the hangingwall and the Oligo-Miocene andesites in the footwall. Considering the top of the acoustic basement (A) the minimum throw is 400 m. It is not possible to assert that this fault was active during Plio-Quaternary time.

From the seismic lines arise that in the southern Campidano the master fault during Plio-Pleistocene times was in the western edge. This is clear mainly in the lines CA-303-92-V and CA-304-92-V (Fig.3.2.2). In fact, although these seismic lines do not reach the western edge fault, the Samassi formation shows a growth wedge-shaped geometry exhibiting an increasing thickness and divergent strata towards the W, suggesting the occurrence of a syn-depositional fault E-NE dipping.

3.2.3 Northern Campidano seismic lines

3.2.3.1 Seismic stratigraphy

The seismic lines acquired in the northern Campidano have been calibrated with the two wells drilled here: Oristano1, that lies on the lines CA-301-92-V, OR-303-92-V, 1, 4 (Fig.3.2.4) and 6, and Oristano2, that is close to the lines 5 (Fig.3.2.4) and 22. In the lines four main reflections have been mapped: the Middle Pliocene erosional surface, the Lower Pliocene erosional surface, the Middle Miocene boundary and the top of the acoustic basement. When clearly observable, the reflection due to the occurrence of the Plio-Pleistocene basaltic lava flows is also picked. The Upper Miocene depositional sequence detected in the wells has not been mapped because its scant thickness of 60 m, that is almost the resolution of the seismic signal.

The uppermost seismic unit (PQ), that coincides with the PQ depositional sequence detected in the Oristano1 and Oristano2 wells, is characterized by parallel continuous even and subparallel continuous reflections, sometimes disrupted. The maximum thickness (1.1 sec TWT) of this unit is reached in the line 2 between the shot points 42 and 44. The parallel reflections detected mainly in the lower part of this unit, can be interpreted as lagoon facies. The continental depositional environment allow to correlate the lower part of this seismic unit (PQ) to the Samassi formation, Middle Pliocene-Quaternary in age. The angular unconformity at the base of the PQ seismic unit, that is the bottom of the Samassi formation, is clear. This unit lies uncomformable above all the underlying units, up to the volcanic acoustic basement.

The underlying seismic unit (LP) is characterized mainly by transparent seismic signal. It reaches the maximum thickness (0.2 sec TWT) in the line 4 between the shot points 140 and 143. The seismic facies suggest a marine depositional environment, in fact is composed by the marine succession of Lower Pliocene age (LP) detected in the Oristano1 and Oristano2 wells. This unit is discontinuous and has not been mapped in all the lines, due most likely to the non-deposition, and in this case an erosional surface should be take place, or because the thickness of the unit is below the seismic resolution. The erosional surface at the base of this unit is very accentuated.

The underlying seismic unit (LMM1) is characterized in the upper part by subparallel wavy disrupted reflections, and in the lower part mainly by transparent seismic signal. It reaches the thickness of 0.5 sec TWT. As detected in the electric logs (Fig.3.1.3) of the Oristano1 well, the seismic facies shows a regressive trend for this unit, with more shallow water marine sediment toward the top. This seismic unit is correlated to the Gesturi marls, Upper Burdigalian-Langhian in age. The LMM1 seismic unit is missing in the northern part of the Campidano of Oristano, as shown by the Oristano2 well. It lies conformable above the LMM2 seismic unit.

The LMM2 seismic unit is characterized by subparallel disrupted reflections in the lower part and mainly by transparent seismic signal in the upper part, showing a transgressive trend of sedimentation for this unit. It reaches the maximum thickness (0.8 sec TWT) in the line 17. It is the lower part (LMM2) of the LMM depositional sequence detected in the Oristano1 well. Thus, the LMM2 seismic unit is correlated to the Marmilla Formation, Aquitanian-Lower Burdigalian in age. As the previuos unit, it is missing in the northernmost sector of the Campidano. It onlaps on the acoustic basement (A).

The deepest unit is the acoustic basement, made up mainly of the Oligo-Miocene volcanic succession. In the central part of the Campidano of Oristano, it is detected at great depth (>2000 m) whereas in the southern and northern part it is more shallow and crops out in the sourrounding areas of the plain, sealed directly, sometimes, by the Plio-Pleistocene basaltic lava flows.

3.2.3.2 Seismic structures

The most important fault, active during Plio-Pleistocene times detected from the seismic lines in the northern Campidano, is clearly observable in the lines 2 (Fig.3.2.5) and 3.

In the line 2 this normal fault (Sinis fault) is detected between the shot points 35 and 40. It dips to the east of 75°. At the surface, the footwall of the fault is the Sinis peninsula, where the Upper Miocene succession crops out sealed directly by the Pliocene basalts. The Sinis fault displaces the base of the PQ seismic unit, that reaches the depth of 1,040 m, and the Pliocene basalts, that reach the depth of 440 m.

In the line 3 the Sinis fault shows the same characteristics that in the line 2. In the line 3, however, the basalt are not detectable, due probably to the poor seismic signal, but the base of the PQ seismic unit is at depth of 660 m.

The northern Campidano is characterized by several normal faults that affected the base of the PQ seismic unit with throws that do not exceed 200 m.

In the seismic line 2, between the shot points 63 and 64, a normal faults dipping to the west of 75° with vertical throw of 120 m, occurs.

Other two normal faults have been detected in the line 3. The first, between the shot points 110 and 111, is E dipping and has a throw of 140 m. The second, between the shot points 97 and 99, is W dipping with a throw of 200 m.

Other normal faults dipping to the W have been detected in the northern sector of the Campidano of Oristano in the seismic lines OR-301-92-V, 5, 20, 22 and 28, with a throw not bigger than 200 m.

The same vertical displacement is detectable for other normal faults recognized in the lines OR-301-92-V, 8, 13 and 30, but dipping to the E.

The seismic lines acquired in the southern part of the Campidano of Oristano show normal faults that affect both the PQ seismic unit and the Pliocene basalts. The throw of these faults does not exceed 200 m.

In the lines OR-302-92-V, 7, 12, 15, 18 and 23, the normal faults dip to the E, in the lines CA-301-92-V, OR-302-92-V, OR-304-92-V, 7, 9 and 12, dip to the W.

The line 17 (Fig.3.2.5), oriented N-S, shows as both the Miocene and Pliocene basins became deeper towards the Oristano Gulf, where unfortunately seismic lines have not been acquired. In this line the erosional surface at the base of the Samassi formation (PQ) reaches 900 m of depth, the base of the Lower Pliocene marine succession (LP) 1,100 m, and the top of the volcanic basement (A) more than 2,000 m. Towards the S, instead, the volcanic basement is shallower and small outcrops occur in the Campidano plain close to Pabillonis village.

From the above described evidence arise that the Plio-Pleistocene master fault in the northern Campidano is, as in the southern, located in the western edge. Even though this fault is detectable only in two seismic lines (lines 2 and 3) and the Samassi formation (PQ) does not show clear evidence of syn-tectonics deposits, this can be confirmed by the thickness of the Plio-Pleistocene succession that increases westward and by the Plio-Pleistocene basaltic lava flows that dip to the W and look displacedrespect to the same flow that crop out in the Sinis peninsula.

Unlike the southern Campidano, it would seem that no recent faults occur in the eastern edge, as the eastward thinning of the Samassi formation demonstrates, up to be missing. In fact, it seems that the basalts of the Monte Arci are the same detected in the seismic lines, tilted by the E dipping Sinis fault.

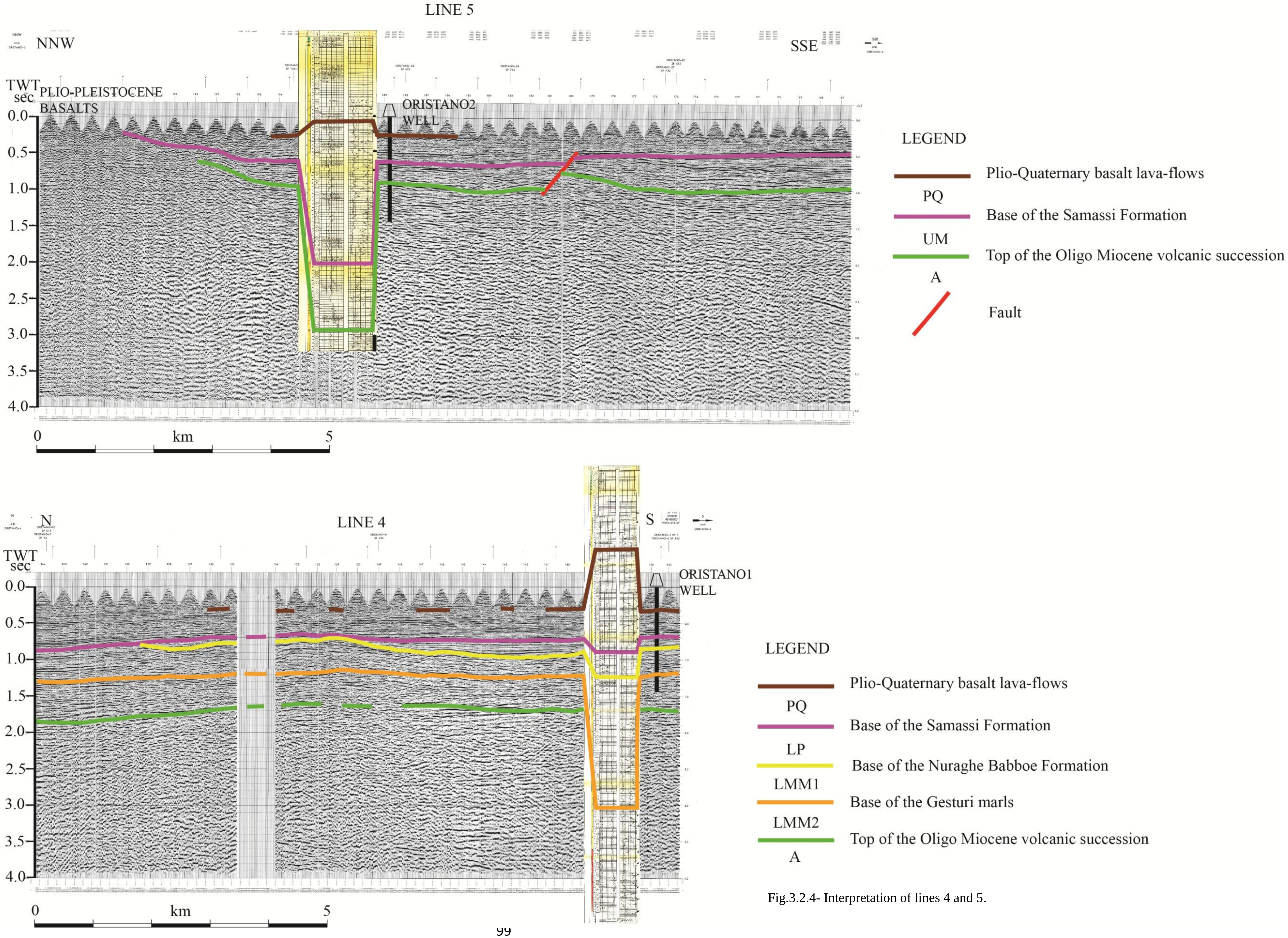


Fig.3.2.4- Interpretation of lines 4 and 5.

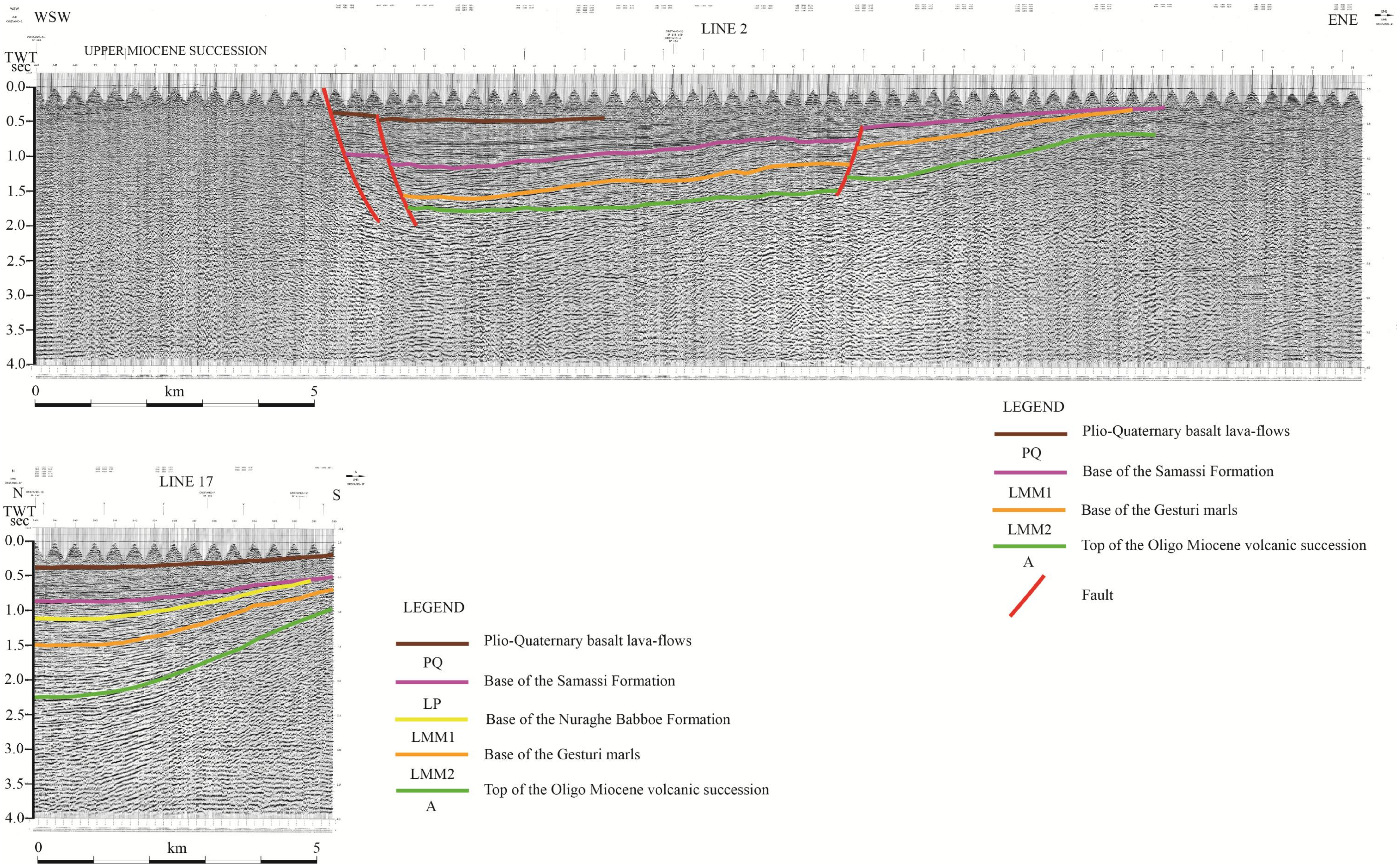


Fig.3.2.5- Interpretation of lines 2 and 17.

3.3 TWT-MAP AND 3D MODEL OF PLIOCENE EROSIONAL SURFACE

3.3.1 Two-way time map of Middle Pliocene erosional surface

Two-way time structural maps of the erosional surface at the base of the Samassi formation have been carried out in both the northern and the southern Campidano. The choice to map this horizon originated because it is a time marker for the Pliocene tectonics that shows a strong continuity in the studied seismic lines. In fact, the other Pliocene time markers, like the erosional surface at the base of the Lower Pliocene succession (Nuraghe Baboe Formation) or the Plio-Pleistocene basalts, are detected only in the northern Campidano and have not continuity in the seismic lines.

The two-way time structural maps have been made by hand to have the maximum control of data to obtain a quality results as best as possible. In the location map of the seismic lines, the two-way time values of the base of the Samassi formation detected in each seismic profile have been plotted with a time interval of 100 milliseconds. The two-way time values of the cut-off points, both of the hangingwall and footwall, are also plotted. Then, the two-way time isolines and the cut-off lines of the faults have been drawn using the interpretive contouring method, that allows to reflect the understanding of the geology of the interpreter, rather than geometrical techniques as equal-spaced or parallel contouring, and honouring as best as the data achieved from the seismic interpretation, surface geology and other geophysical data. Once that the maps was drawn, it has been scanned and imported into ArcGIS10, where it was georeferenced and digitized. Due to the velocity of the waves in the Plio-Quaternary succession (2 km/sec), the values in milliseconds can be directly read as depths in metres.

3.3.1.1 Two-way time map of Middle Pliocene erosional surface in the southern Campidano

The two-way time structural map of the erosional surface at the base of the Samassi formation in the southern Campidano (Fig.3.3.1) shows two normal faults that bound both the eastern and western edge. Only the hangingwall cut-off lines of these faults can be draw, because the boundary mapped is missing in the footwall blocks, making it impossible to evaluate the true heave and throw values.

As already said in the previous paragraph, the fault in the western edge (Capoterra Fault) is not well visible in seismic profiles, but in lines CA-304-92-V, CA-303-92-V and LINE04 the Samassi formation shows a growth wedge-shaped geometry exhibiting an increasing thickness and divergent strata towards the W, suggesting the occurrence of a syn-depositional fault E-NE dipping. In addition to this, the Bouguer anomaly map by BALIA *et alii* (1984) (Fig.1.4.2) shows that on the western border the gravity contour lines are oriented parallel to the graben axis, suggesting the occurrence of a fault roughly parallel to the graben axis. This fault does not clearly crop out in the field because buried under recent clastic deposits but its occurrence is inferred by the NW-SE alignment of the Paleozoic basement and Oligo-Miocene volcanic outcrops (Fig.1.2.1). The throw of this fault is more than 600 m. Considering that the Middle Pliocene erosional surface at the base of the Samassi formation is missing in the footwall a greater throw can be supposed.

The fault along the eastern edge (San Sperate fault) strikes NW-SE from Elmas to northwest of San Sperate and N-S from northwest of San Sperate to Serrenti, it is clearly visible in lines 02, 01, CA-303-92-V, 08 and 04 (paragraph 3.2.2). In these lines the occurrence of a rollover anticline, which affects both the Samassi formation and the pre-Pliocene succession, is shown. The two way time structural map shows that the fold axis dips to the SE of less than 1°. Instead, the line CA-301-92-V is parallel to the strike direction of the fault, therefore is not easy to recognize the rollover anticline and the fault, which is suggested by the NW-SE alignment of the Miocene marine outcrops along the eastern edge of the trough (Fig.1.2.1). Because in the footwall the reference level is missing, the throw of this fault is certainly more than 500 m in the oriented NW-SE sector of the fault and becomes less northward, less than 100 m in the N-S oriented sector of the fault.

A third fault (Samassi fault), clearly visible in seismic lines CA-302-92-V, 03, 09 and 02, occurs in the central part of the trough, approximately from north of Samassi to north of Villasor. For this fault, unlike those on the edges of the trough, it has been possible to map also the footwall cut-off line, thus the true values of throw and heave can be estimated. This fault is oriented N-S and dips to the W. North of Villasor the fault bifurcates into two faults: the first strikes N-S and dips to the E and the second strikes NW-SE and dips to the SW. Between these two faults occurs another rollover anticline. The fold axis dips to the NW of less than 1°. The maximum throw of this fault reaches 680 m considering the Middle Pliocene erosional surface at the base of the Samassi formation in both the footwall and hangingwall of the fault. The footwall block of this fault is equivalent to a N-S elongate positive gravity anomaly, from Villasor to Samassi (BALIA *et alii*, 1984; Fig.1.4.2). Furthermore, this fault is located exactly in the subsurface below the Flumini Mannu river. This can suggests that the Samassi fault influences the hydrography and then that could be active in more recent times.

The normal fault detected in the line 04 can not be correlate with other fault interpreted in other seismic lines, thus, the strike and the length were deducted avoiding to intersect other seismic lines. This fault strikes NW-SE and dips to the NE, with a total throw of 300 m.

The maximum depth of the erosional surface at the base of the Samassi formation in the southern Campidano is 900 m, in the subsurface below Decimomannu. In the two-way time contour lines map, where the geometries of the Middle Pliocene erosional surface are not related to the development of the faults, like the gentle rollover anticlines, it shows a "gently rolling landascape", typical of erosion and planation surface developing in continental environment, similar to the surface that, in closest area, cuts the Miocene succession and is sealed by Pliocene lava flows (FUNEDDA *et alii*, 2012).

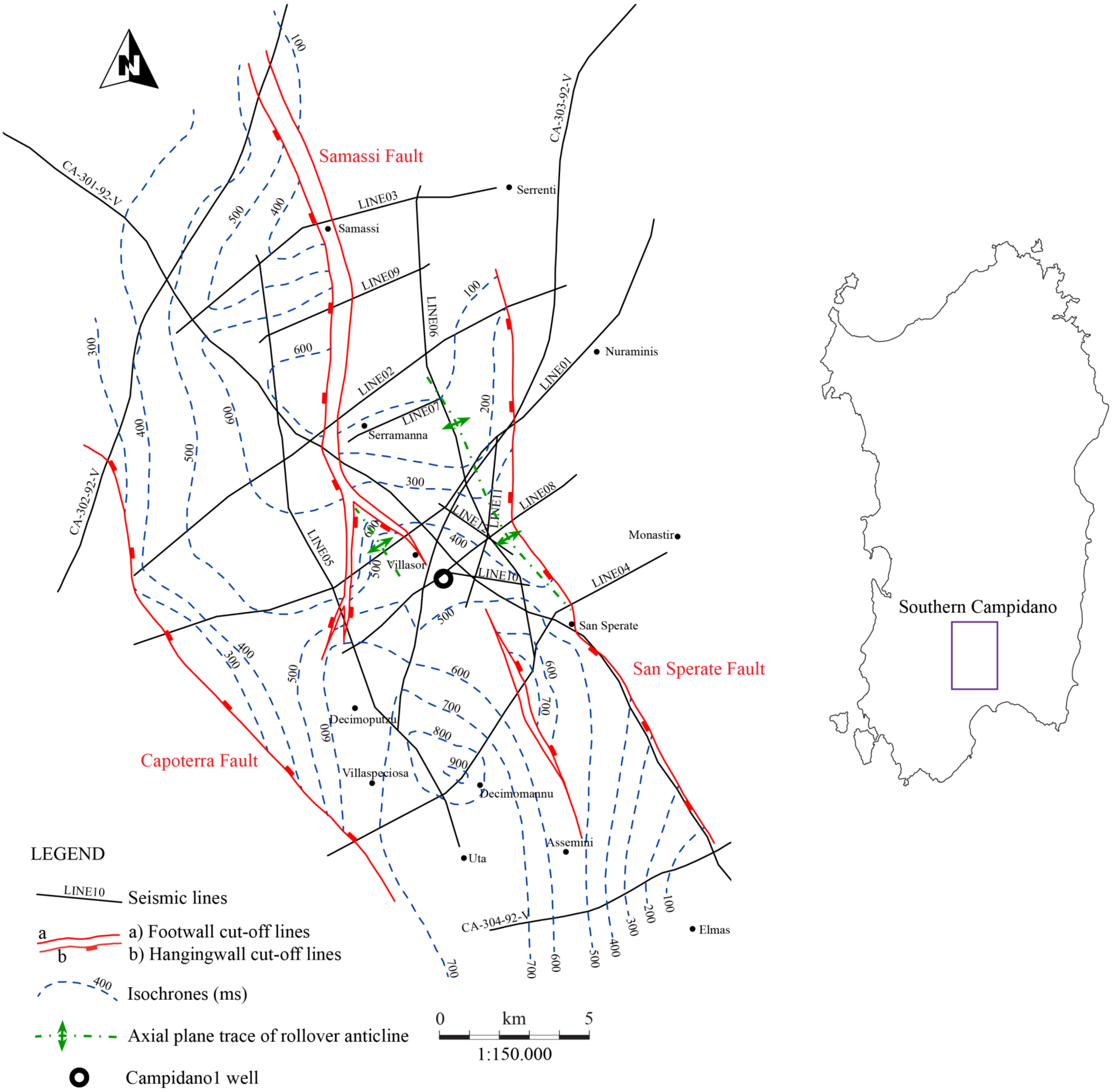


Fig.3.3.1- Two way time structural map in the southern Campidano of the Middle Pliocene erosional surface at the base of the Samassi formation.

3.3.1.2 Two-way time map of Middle Pliocene erosional surface in the northern Campidano

The master fault (Sinis fault) (Fig.3.3.2) in the northern Campidano is located to the east of the Sinis peninsula, where crops out the Upper Miocene succession sealed by the Plio-Pleistocene basalts. It is oriented roughly N-S and dips to the E. As said in the previous chapter, this fault is clearly detectable in the seismic lines 2 and 3. Although no seismic lines were acquired in the Gulf of Oristano, the southern part of this fault can be located just to the east of the Capo Frasca peninsula, considering the occurrence, here, of the same stratigraphic succession of the Sinis peninsula, that is those of the Upper Miocene sealed by the Plio-Pleistocene basalts, and, southward, the tectonic contact between the metamorphic Paleozoic basement and the Oligo-Miocene volcanites. The central part of the fault is achieved joining the northern and southern segments. The throw of this fault is more than 1,100 m. Because the base of the Samassi formation is missing in the footwall, this fault is represented in the two way structural map only by the hangingwall cut-off line, thus, the throw is the minimum measurable.

The southern sector of the Campidano of Oristano is characterized by N-S trending fault, with length that does not exceed 5 km and total throw that rarely exceeds 100 m. Some of these faults are synthetic and others antithetic in respect to the master fault, dipping to the east and to the west respectively.

The same is to the northern sector of the Campidano of Oristano, where the other faults detected rarely reaches 200 m of total throw and exceed 5 km in length. The strike of these faults tends to change from N-S to NNW-SSE northward.

As in the southern Campidano, the mapped surface shows a "gentle rolling landscape". The basin infilled by the Middle Pliocene succession has an irregular basal surface, characterized by a deeper zone elongated N-S on the western edge bounded by the Sinis fault, where the Plio-Quaternary succession reaches the main depocenter (1,100 m below the sea level). In the center part of the two-way time map the surface is really irregular, probably for the occurrence of several faults. In the eastern side it becames shallower up to crop out in the northeast part close to Villanova Truschedu village.

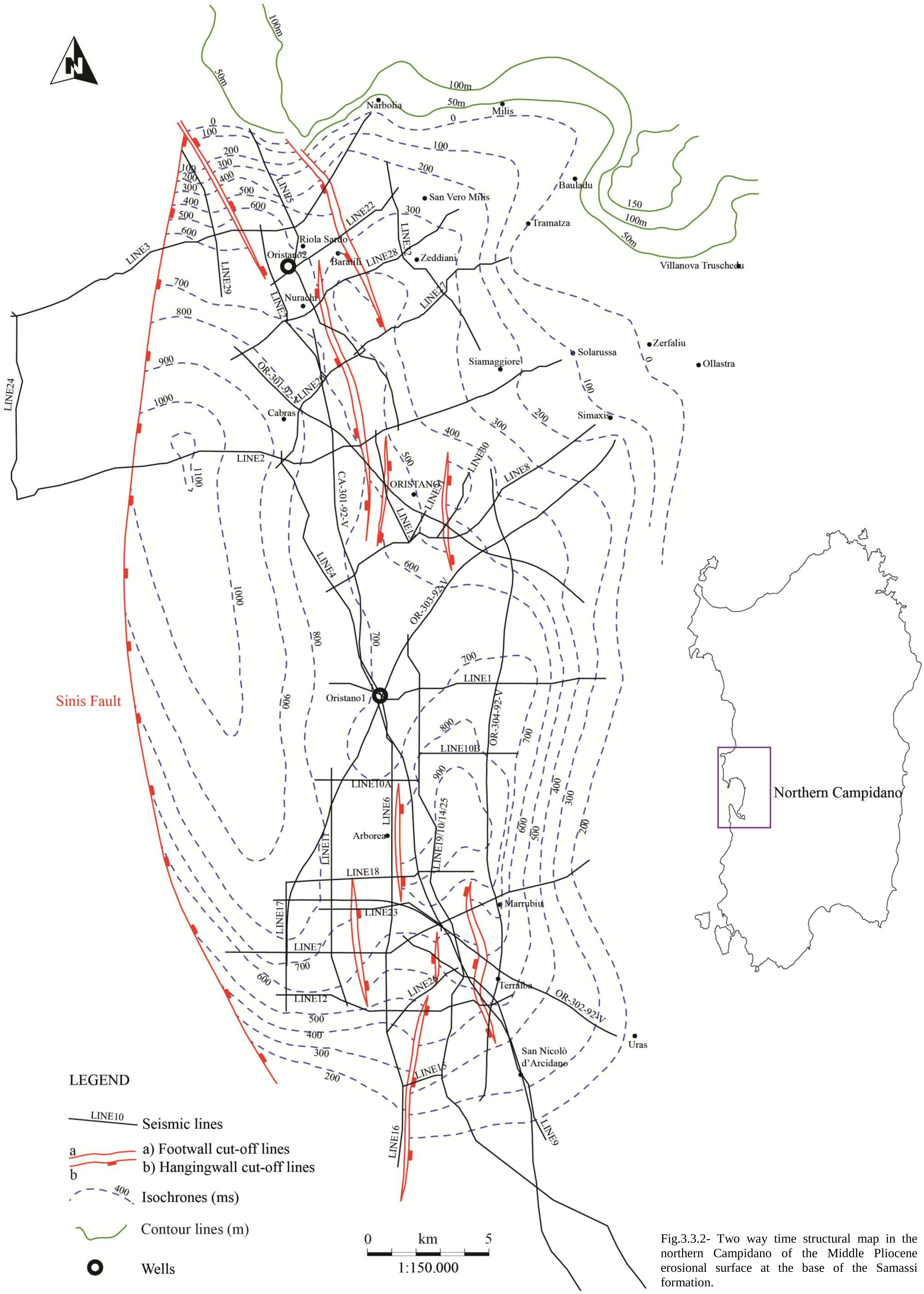


Fig.3.3.2- Two way time structural map in the northern Campidano of the Middle Pliocene erosional surface at the base of the Samassi formation.

3.3.2 3D model of the Middle Pliocene erosional surface

The 3D model of the erosional surface at the base of the Samassi formation has been carried out with the 3D geological modeling software MOVE of the Midland Valley.

The model is constituted by the surface and the structure that affected it. To build the surface the two way time structural maps described above have been used, which have been previously digitized and georeferenced using ArcGIS, whereas the fault surfaces have been achieved interpolating the fault lines interpreted in the seismic lines. Once that the two way time structural maps were imported into MOVE as shape files, the depth values were assigned to every isoline and to the intersection points of the cut-off lines with the isolines in the "Attribute Analyser" of the "Object properties", so as to have the projection of the isolines and cut-off lines of the maps in depth (Fig.3.3.3).

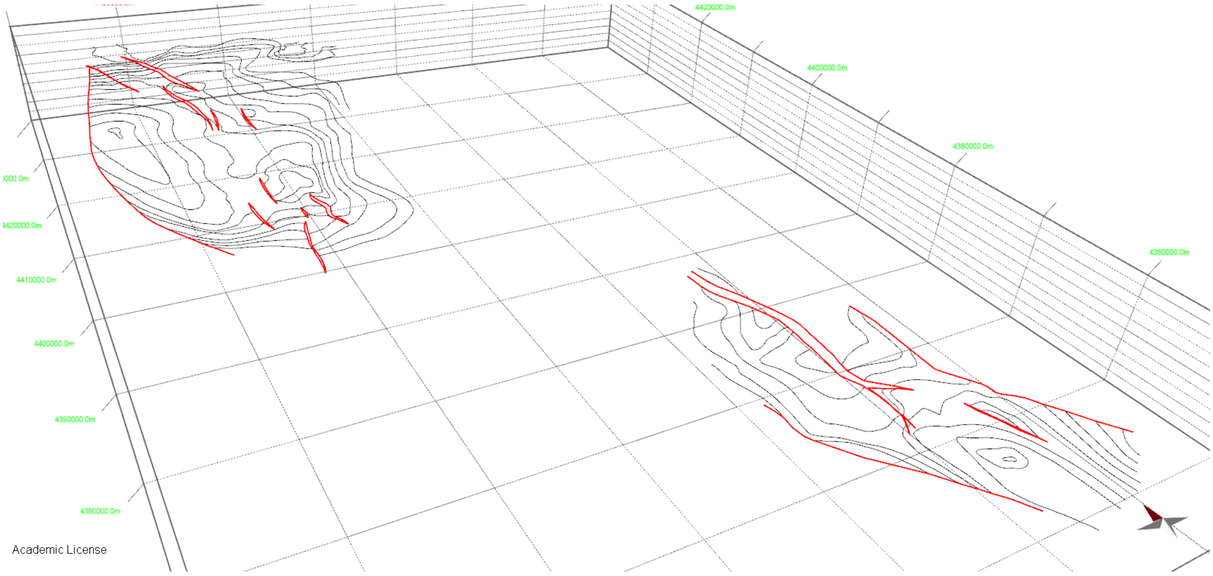


Fig.3.3.3- Two way time structural map imported into MOVE displayed in 3D view.

Interpolating both the isolines and the cut-off maps, using the "Delaunay triangulation" algorithm in the "Model building-Build surface from lines" toolbox, the surface of the erosional surface at the base of the Samassi formation has been built (Fig.3.3.4).

To complete the 3D model the faults affecting the surface were added to the model. To build the faults surfaces to have them georeferenced together with the built erosional surface the location map of the seismic lines was imported from ArcGIS into MOVE. Afterwards, the seismic lines polylines were converted in "Section trace", allowing to import the seismic lines raster files. Once that the seismic lines are located in their 3D space, it is possible to interpolate the fault lines interpreted in the seismic lines to build the fault surfaces (Fig.3.3.5 and Fig.3.3.6), using the "Linear" algorithm of the "Model building-Build surface from lines" toolbox. Clearly, the built fault surfaces have to honour the cut-off lines too. Furthermore, the erosional surface has been split with the faults surfaces to create the gaps between the hangingwall and footwall cut-off lines.

Finally, the 3D model (Fig.3.3.7 and Fig.3.3.8) is ready to be used for the following steps of the study: the extension and paleostress calculation.

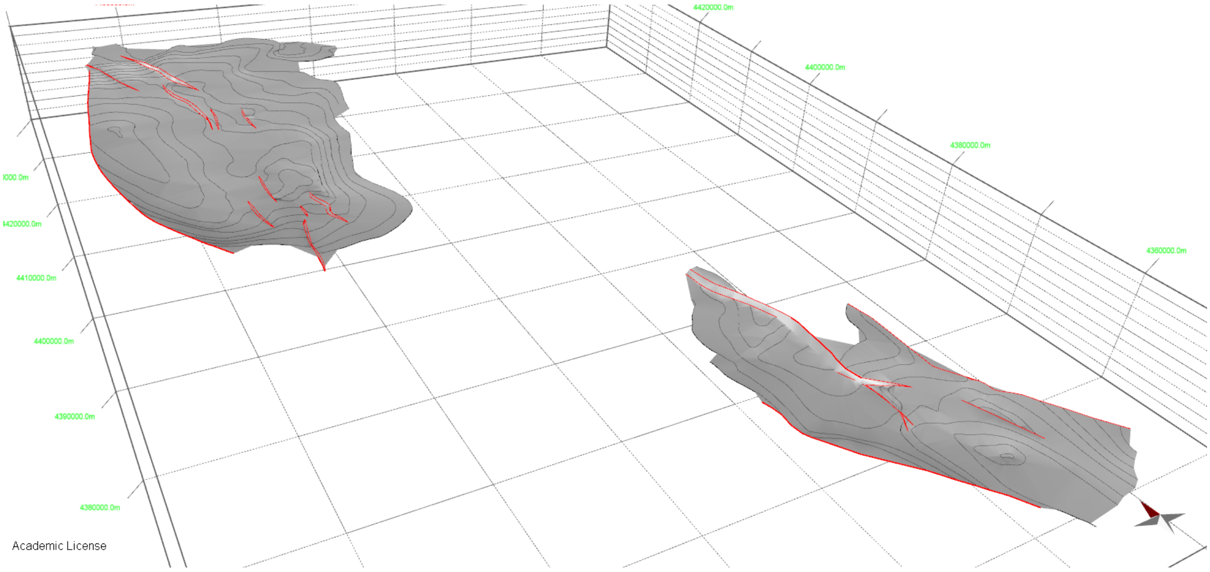


Fig.3.3.4- 3D model of the Middle Pliocene erosional surface at the base of the Samassi formation.

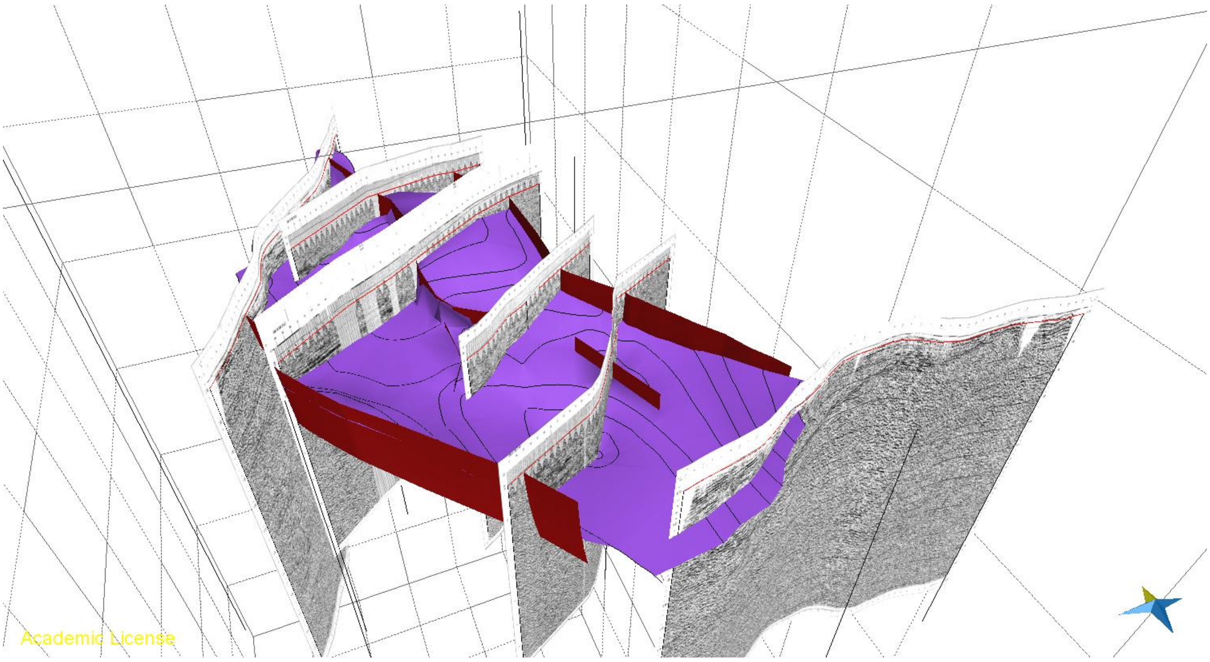


Fig.3.3.5- 3D model of the Middle Pliocene erosional surface at the base of the Samassi formation and the faults that affect it built interpolating the fault lines interpreted in the seismic profiles. Southern Campidano.

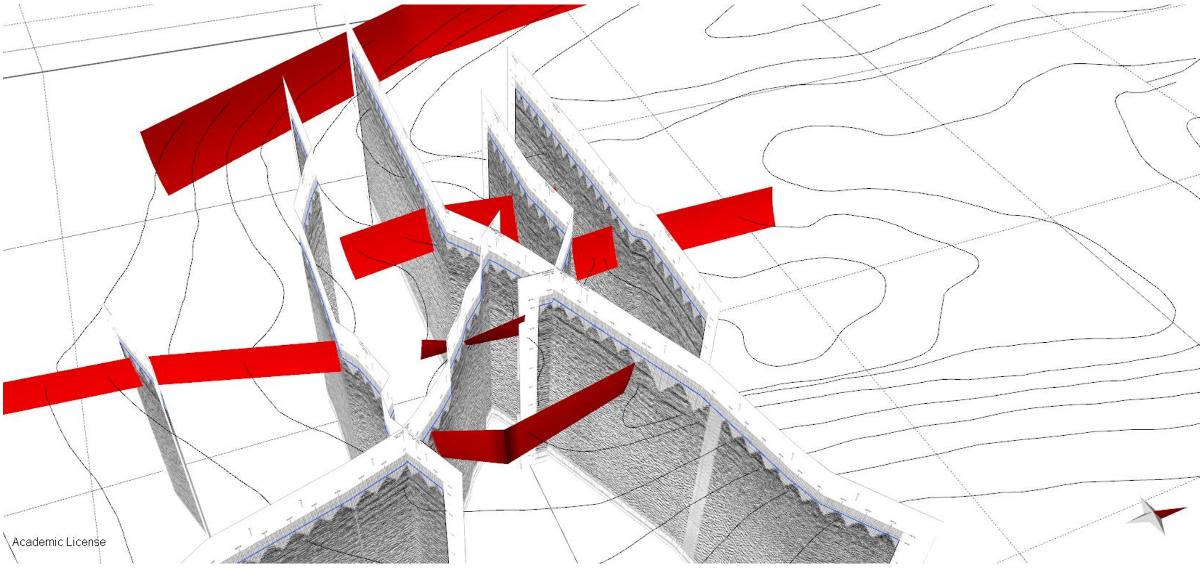


Fig.3.3.6- Faults surfaces, in the southern sector of the Campidano of Oristano, built interpolating the fault lines interpreted in the seismic profiles.

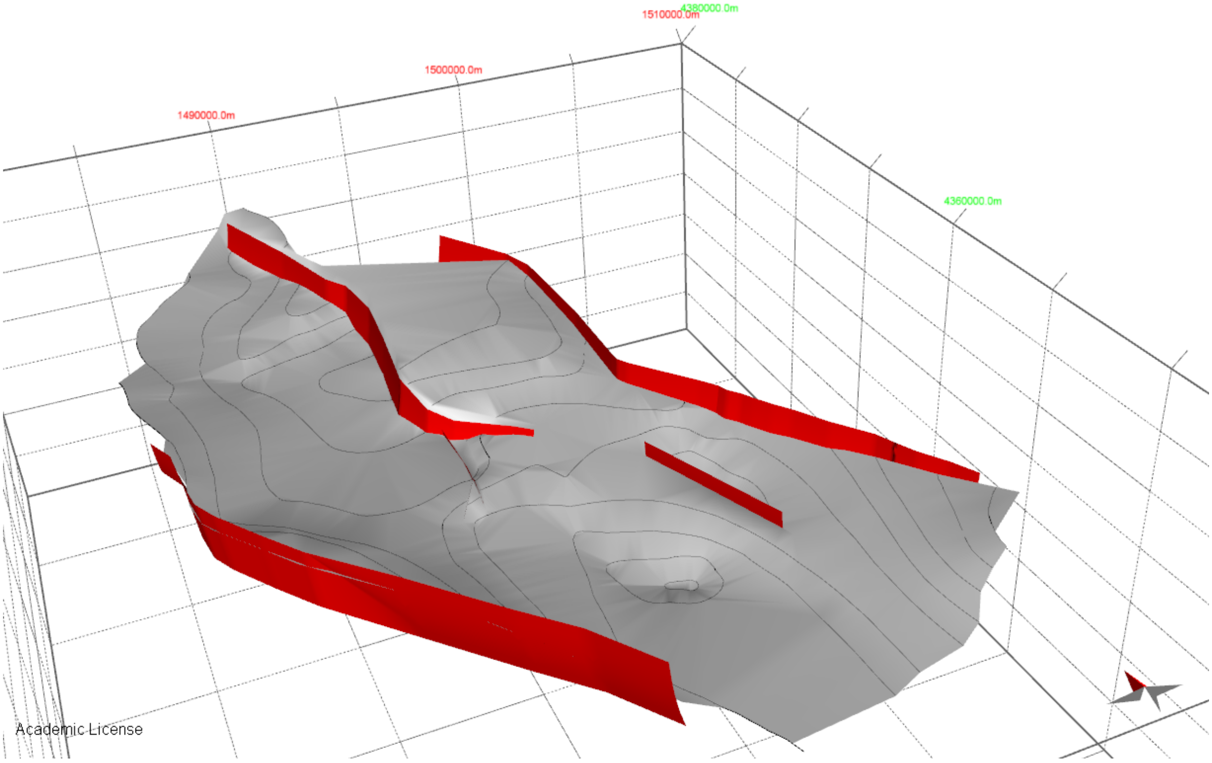


Fig.3.3.7- 3D model of Middle Pliocene erosional surface in the southern Campidano. Vertical exaggeration x2.

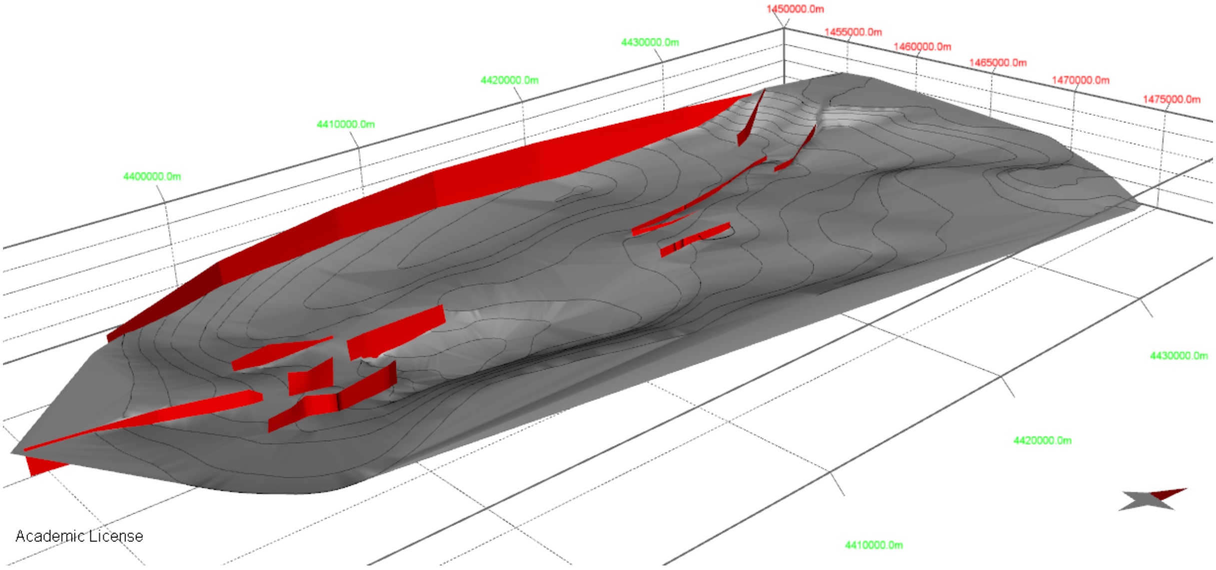


Fig.3.3.8- 3D model of the Middle Pliocene erosional surface in the northern Campidano. Vertical exaggeration x2.

3.4 EXTENSION AND DEFORMATION RATES IN THE CAMPIDANO AREA DURING PLIO-PLEISTOCENE TIMES

The extension affecting the Campidano area has been measured restoring several cross-section extrapolate from the 3D model, described in the previous chapter, of the Middle Pliocene erosional surface at the base of the Samassi formation. In fact, this erosional surface, which can be dated more or less at 3.5 Ma (see chapter 3.1), is an excellent time-marker to describe and quantify the deformation during Plio-Pleistocene times, considering the continuity this surface shows in the subsurface. Unfortunatly, despite the structures affecting the erosional surface and the Samassi formation allow to refer certainly to tectonics Plio-Pleistocene in age, the deformation values measured are the minimum possible, due to two main causes: the first is that the erosional surface, sealed in subsurface at 3.5 Ma, is missing in both the western and eastern "horsts" of the Campidano graben, thus, the maximum extension values measurable are achieved restoring the erosional surface to the intersection of the western or eastern edges faults with the topographic surface; the second is that the faults that do not displace Plio-Pleistocene time-markers, for example those that in the eastern edge, close to the Monastir village, has in the footwall the Oligo-Miocene andesites and in the hangingwall the Langhian Gesturi marls, can not be related certainly to Plio-Pleistocene tectonics and is not possible discern how much of the amount of deformation is related to the previous tectonics phases. Thus, the extension suffered during Plio-Pleistocene could be larger than has been calculated.

To achieved the most reliable as possible extension values, the cross-sections have been realized perpendicular to the main structures (Fig.3.4.1). Six cross-sections have been carried out in the northern Campidano, trending E-W, and then in the southern Campidano, the seven southernmost trending NE-SW and the three northernmost trending E-W.

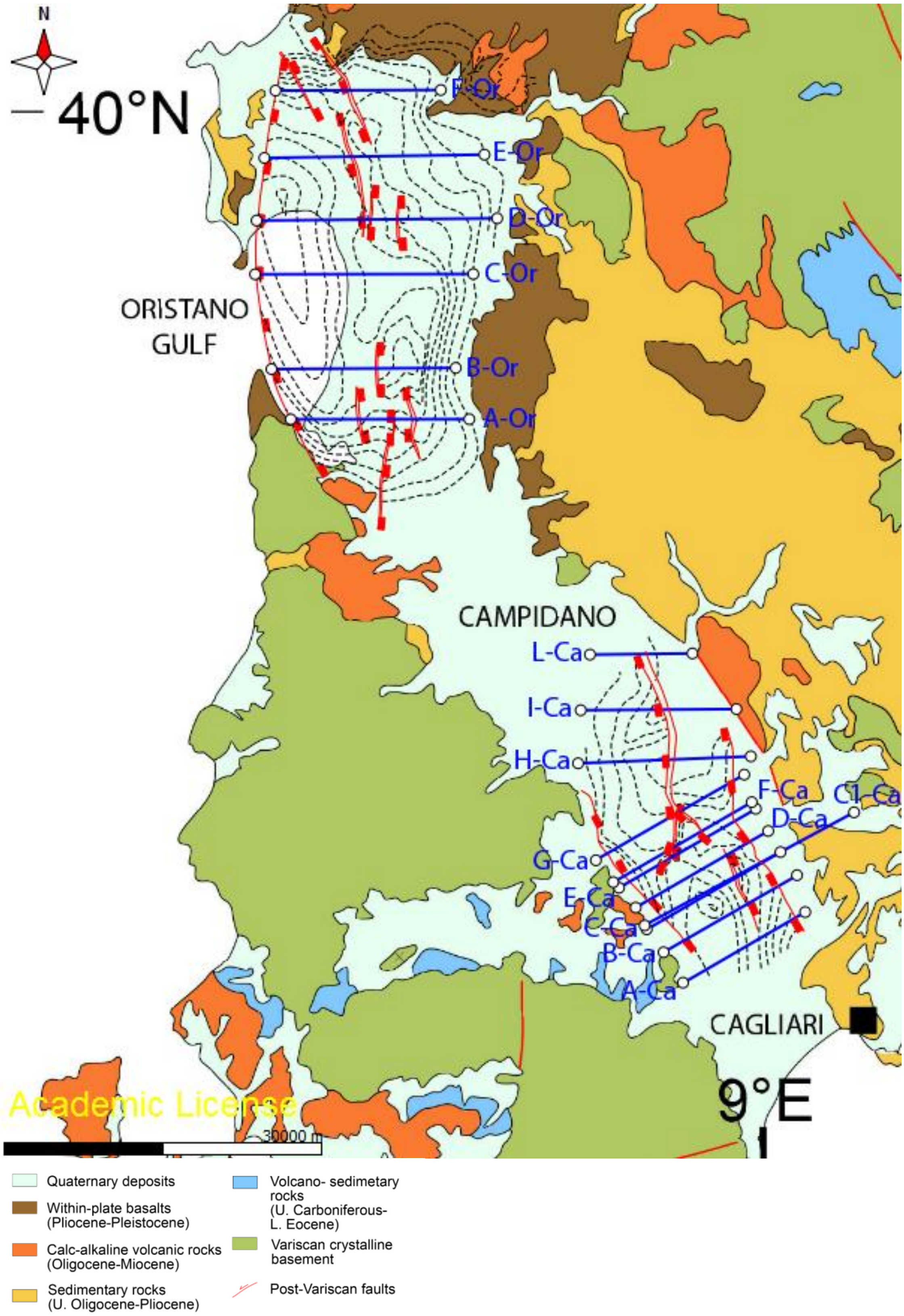


Fig.3.4.1- Location map of the cross-sections. The two-way time structural maps of the erosional surface at the base of the Samassi formation are also shown (Geological map modified from OGGIANO *et alii*, 2009).

Before to construct the cross-sections from the 3D model, the DEM surface of the Campidano area was imported into MOVE, to have the topographic reference to which extend the edges faults, since the seismic lines datum plane is the mean sea level. Then, in map view, the sections trace have been digitized and named. In the section view of every new section trace created the intersections of the surfaces of the model (erosional surface at the base of the Samassi formation, faults and DEM) with the section plane have been collected to create the cross-sections with the lines that are the same of the intersections but these are now permanent objects fully editable in each sections. At this point, every cross-section is ready to be restored (Fig.3.4.2).

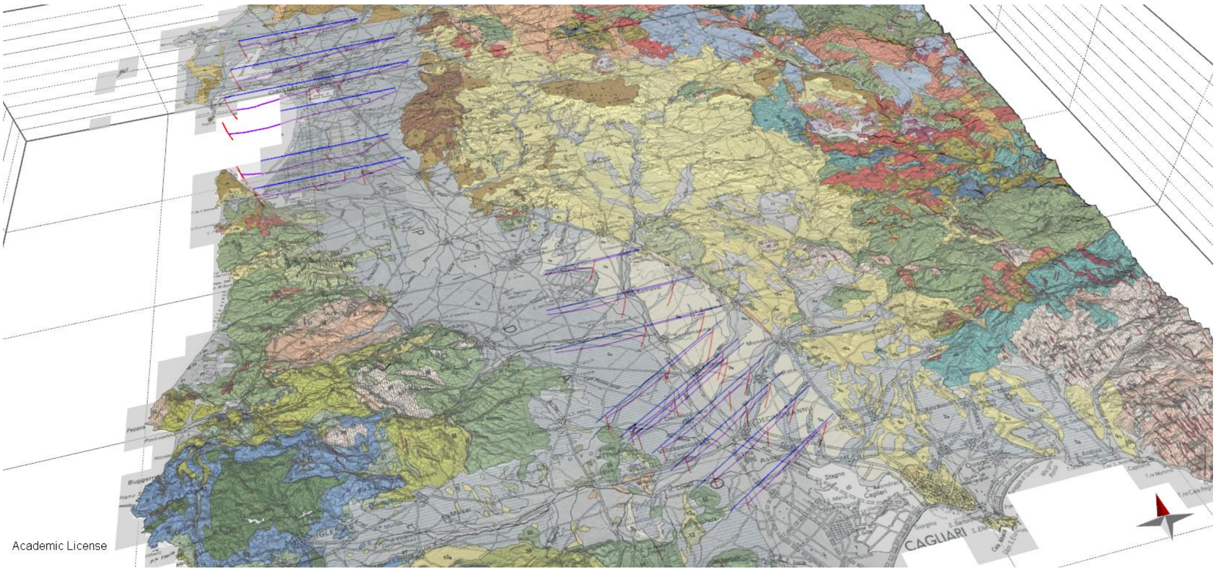
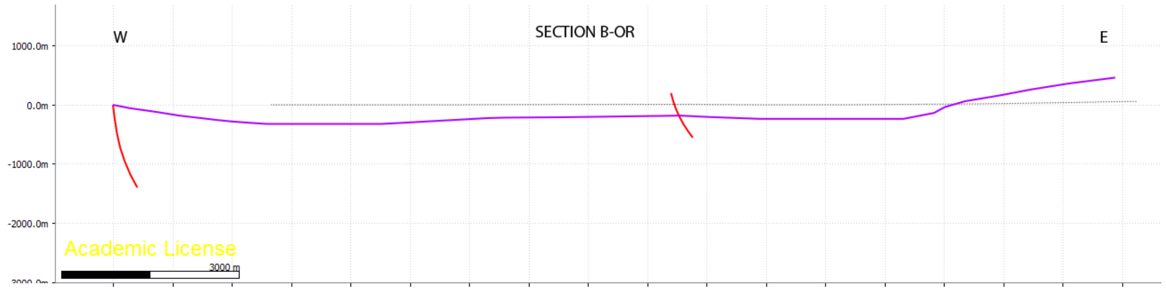


Fig.3.4.2- Southern Sardinia DEM and geology (geological map from CARMIGNANI *et alii*, 2001), 30% transparent, with the cross-sections achieved from the 3D model of the Middle Pliocene erosional surface. The blue lines are the intersection with the topography, the purple lines the erosional surface and the red lines the faults. Vertical exaggeration x2.

Also the restoration of the cross-sections has been carried out using MOVE, where different algorithms designed to reproduce mechanism of deformation seen in the field can be used. In the "Move on Fault" workflow, the algorithms available to restored cross-sections in areas affected by extension are "Simple Shear" and "Fault Parallel Flow". The chosen algorithm is "Fault Parallel Flow" because, unlike "Simple Shear", the flow paths are created parallel to the faults and maintains line lenght. Thus, having to restore an erosional surface, the shape of the surface, related more likely to the paleotopography than to the deformation in the hangingwall due to the faults, is preserved during the restoration. Then, the extension value (ΔL) is obtained from the difference between the initial length of the cross-section (L_1) and the length after restoration (L_0). Furthermore, the elongation ($e=L_1-L_0/L_0$), expressed as a percentage, and the extension factor ($\beta=L_1/L_0$) were calculated. Clearly, the extension values depend on the heave of the faults where the section crosses the fault, as well as to the absence of faults that was not possible to recognise from seismic data.

3.4.1 Plio-Pleistocene extension

The values achieved from the restored cross-section (Fig.3.4.3) are shown in Tab.3.1. In general, the greater values of elongation occur in the southern Campidano, where the highest value is 5.72% measured in the cross-section C-Ca, whereas in the northern Campidano does not exceed 2.50% in the cross-section F-Or. In the southern Campidano, the higher elongation value of 7.26% shown by the C1-Ca cross-section (Fig.3.4.4), where the top of the acoustic basement and the bottom of the Gesturi marls are also shown, is achieved supposing that the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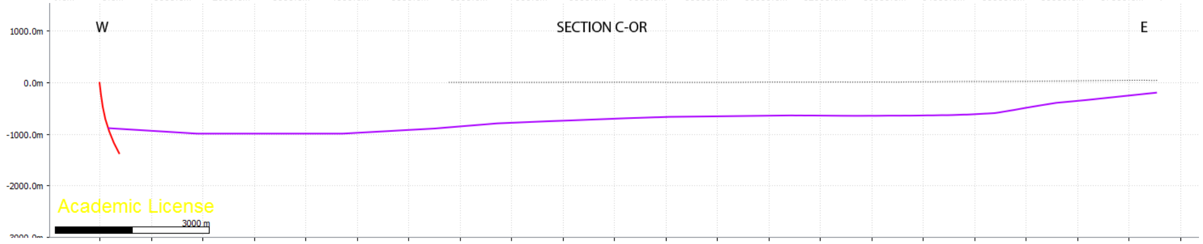
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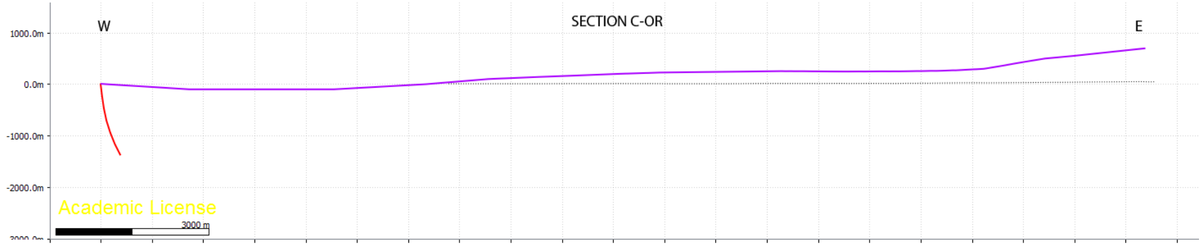
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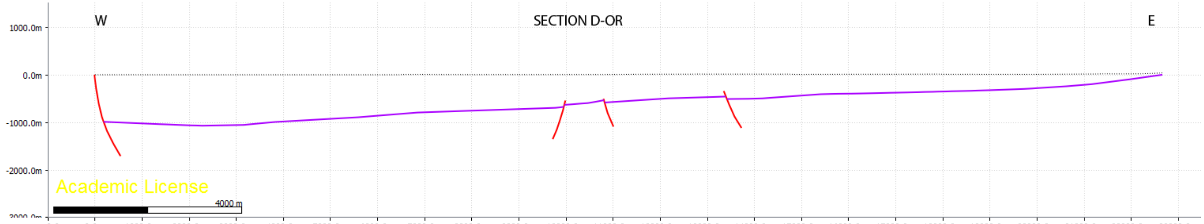
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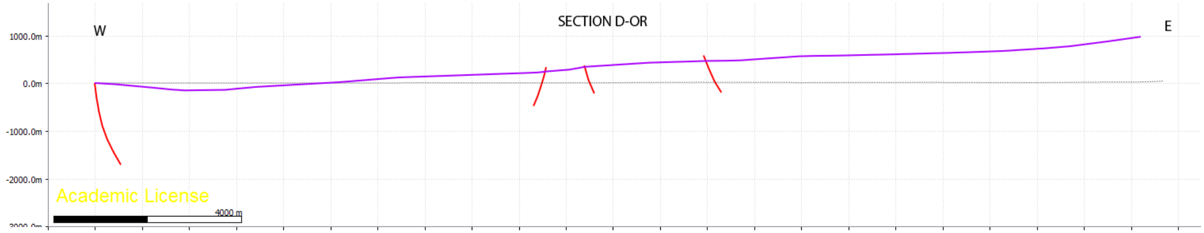
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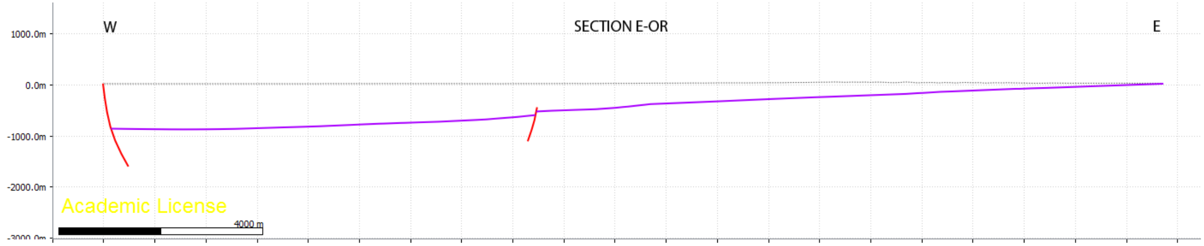
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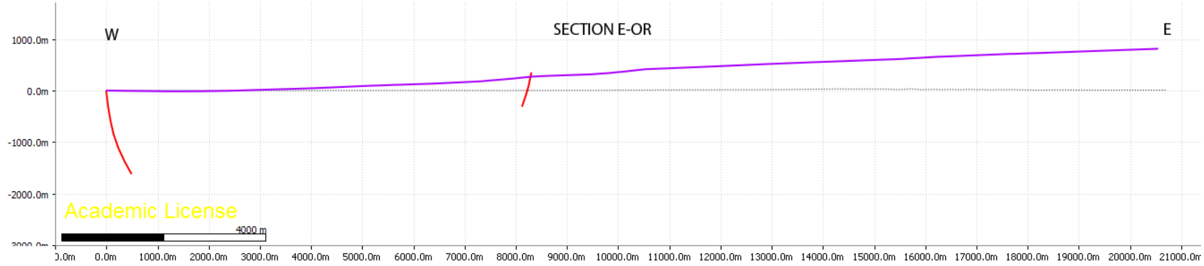
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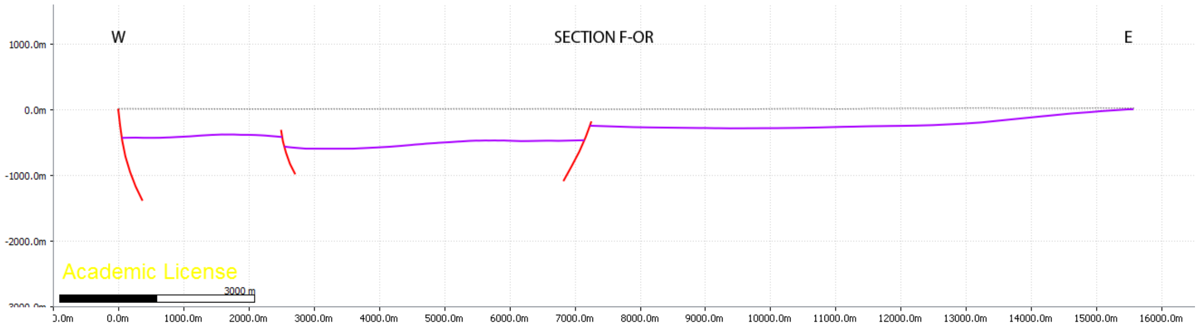
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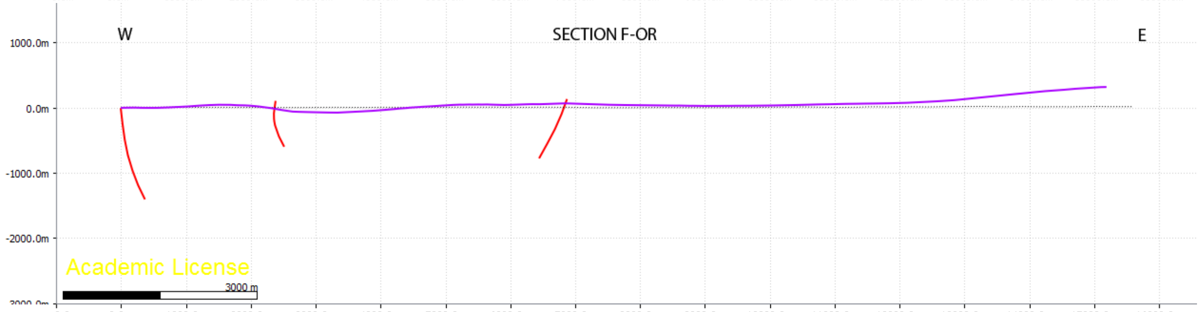
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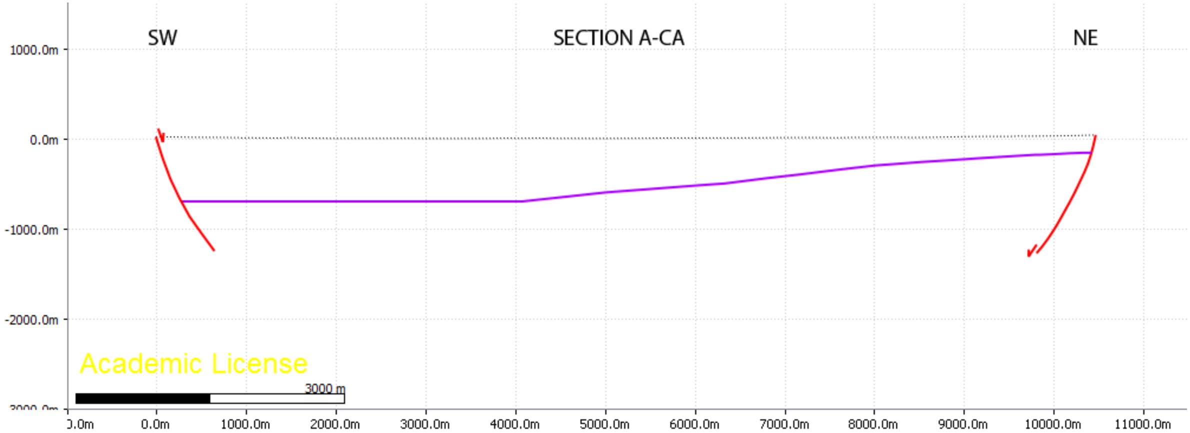
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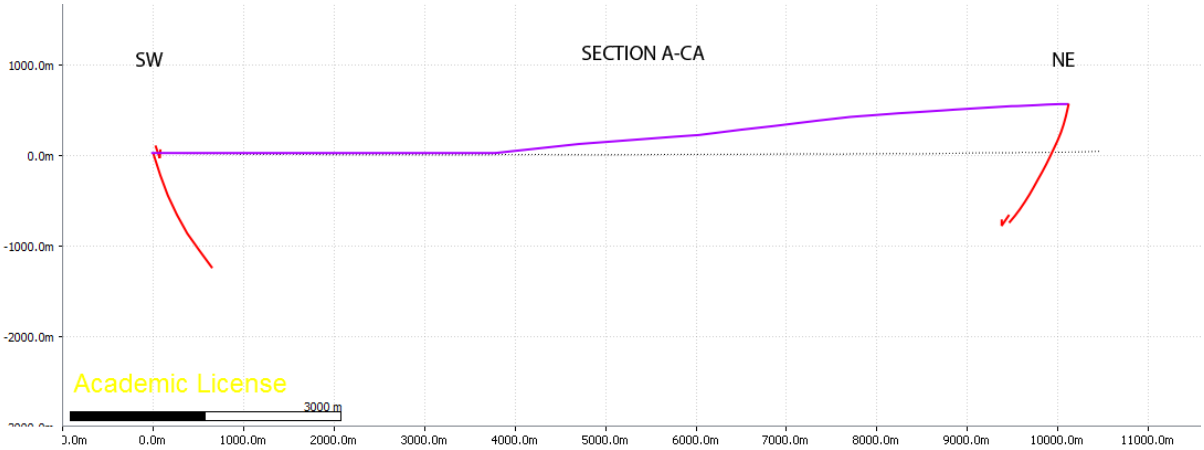
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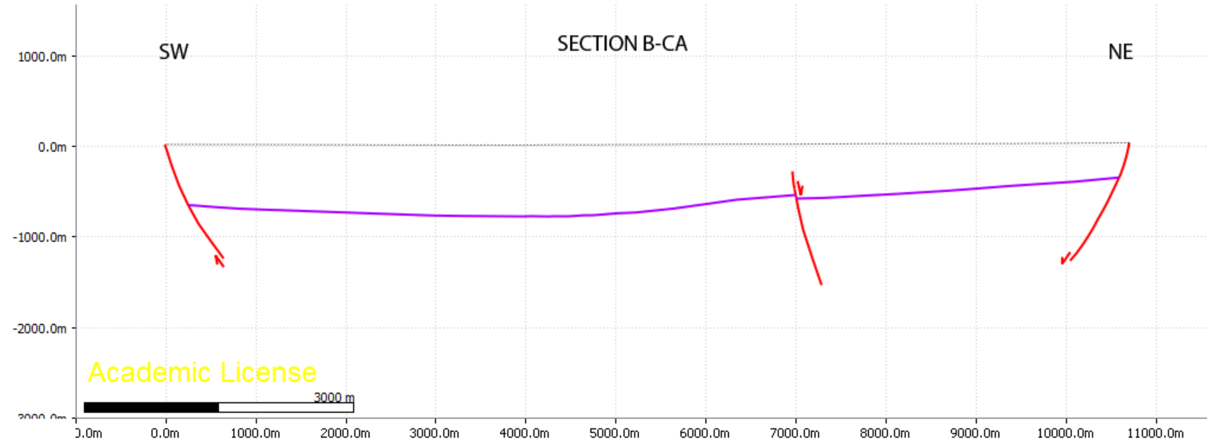
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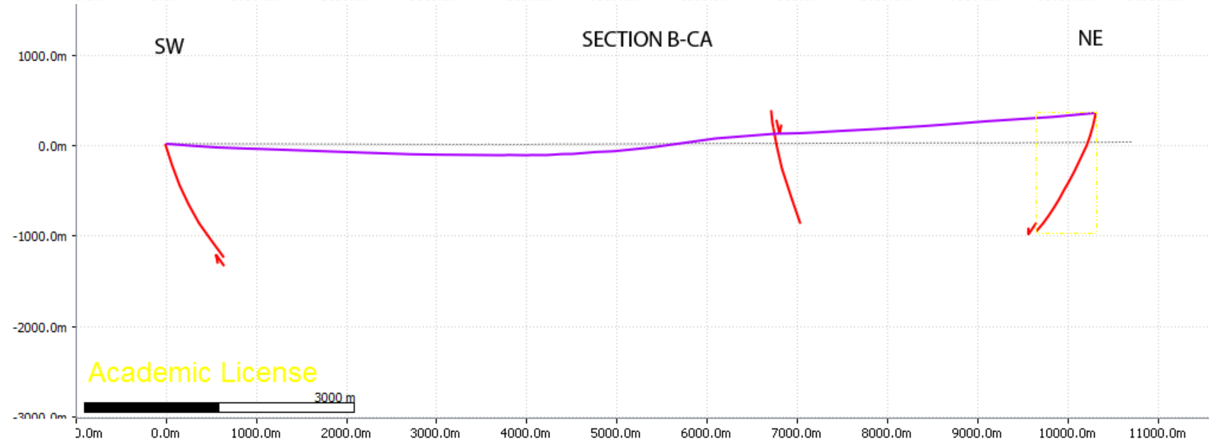
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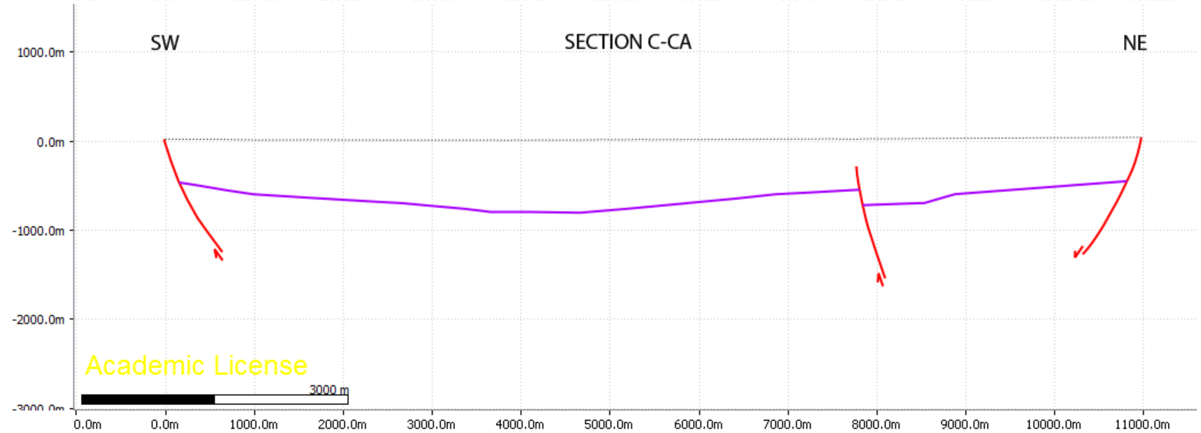
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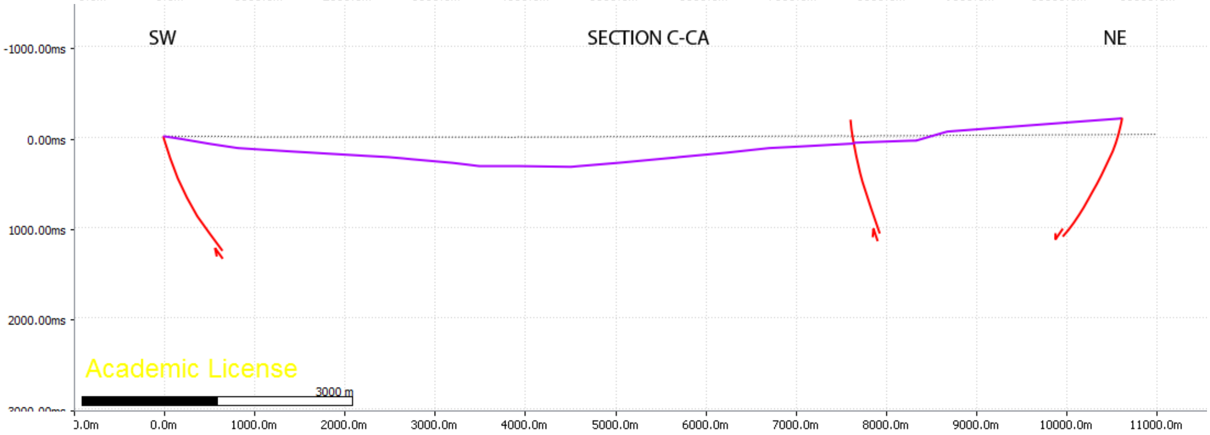
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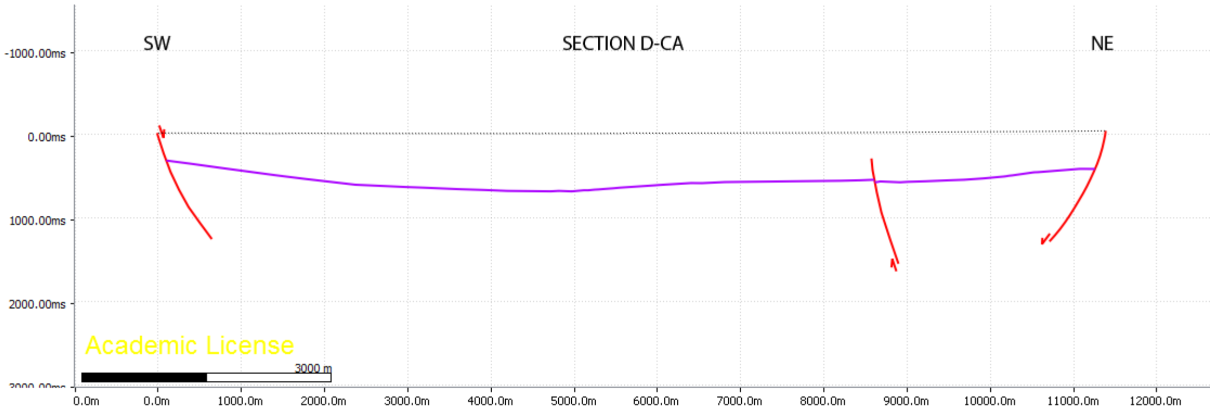
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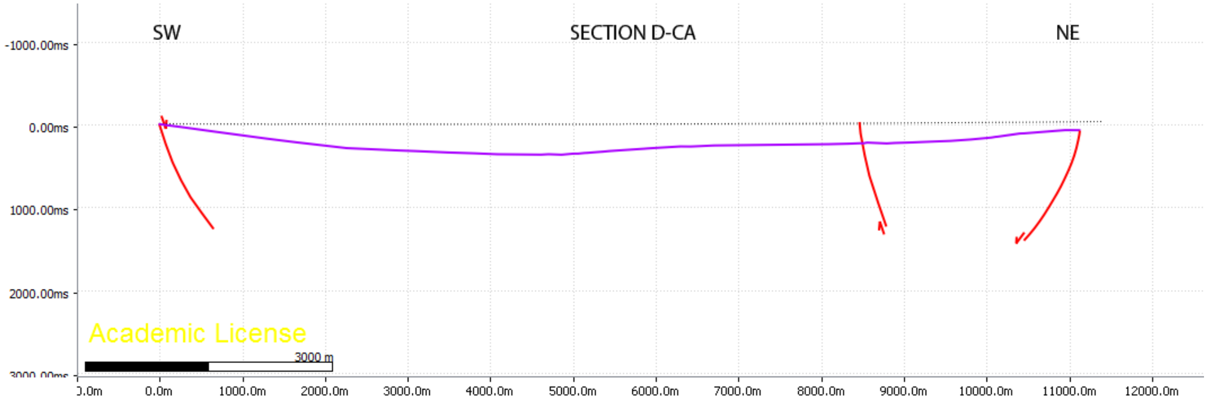
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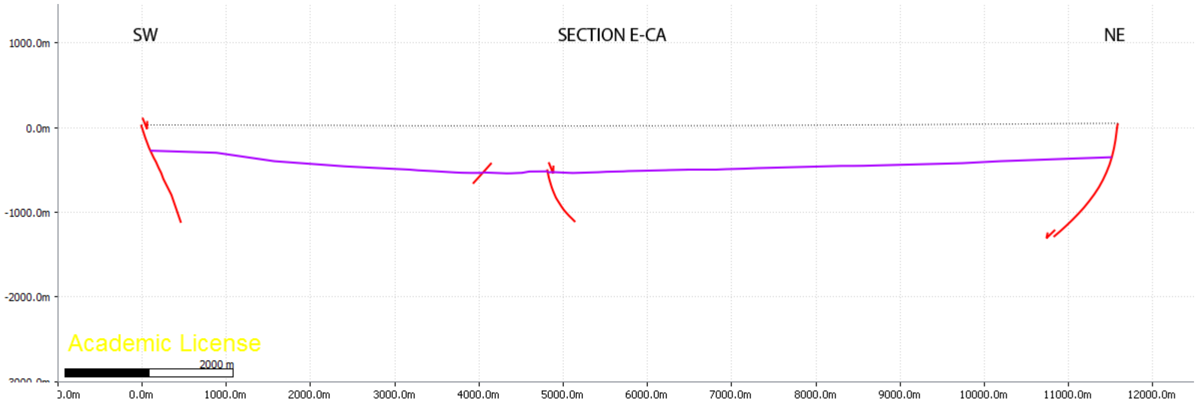
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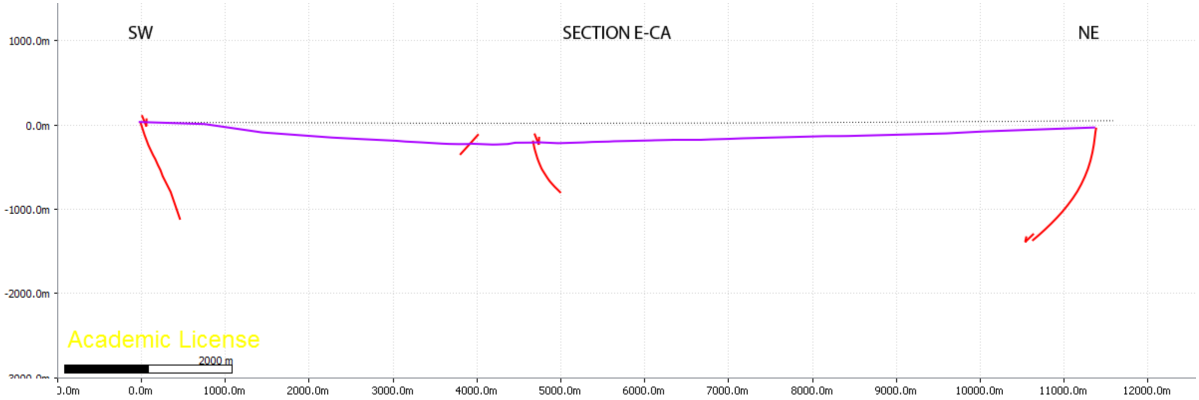
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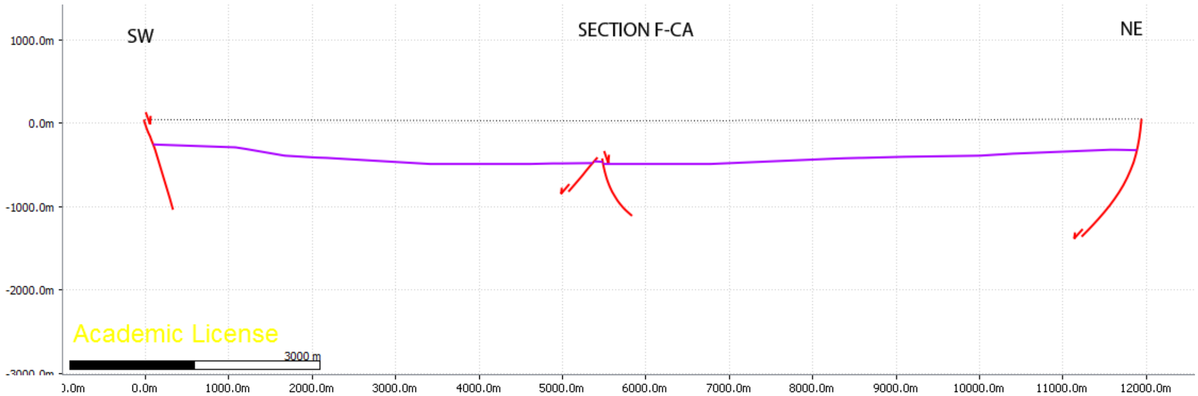
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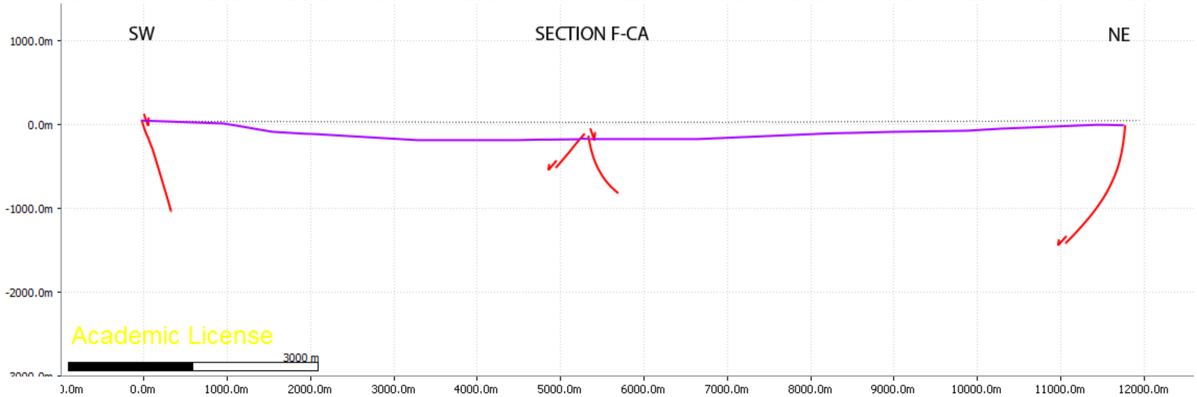
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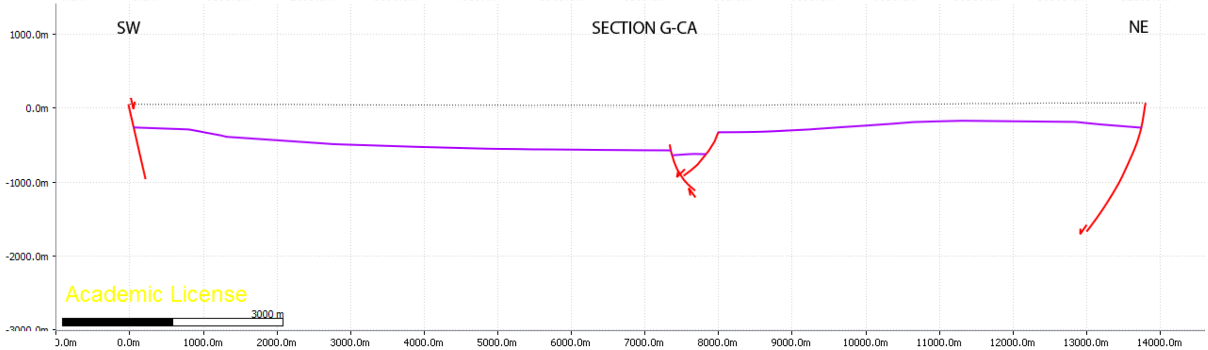
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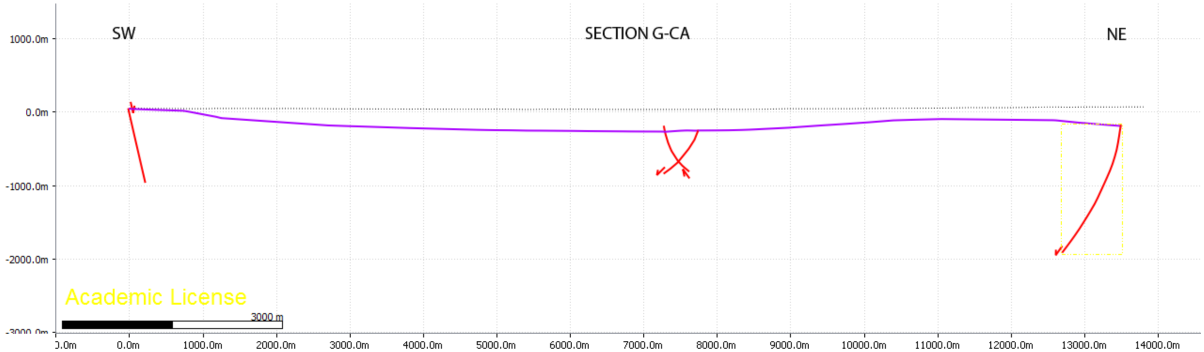
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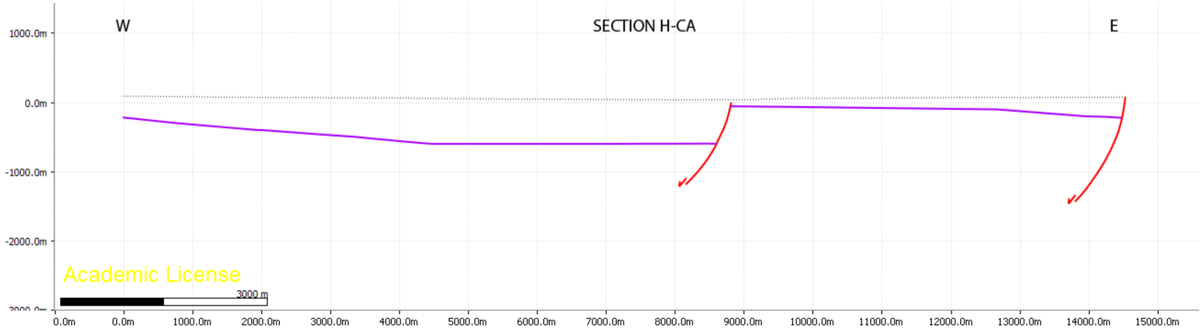
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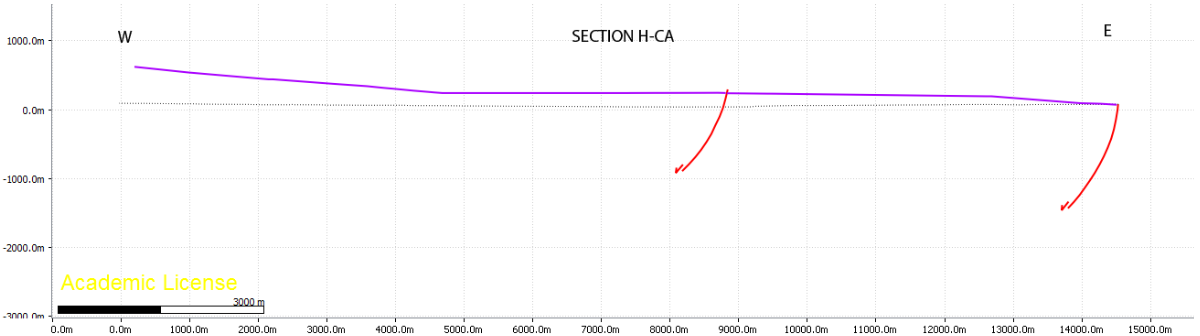
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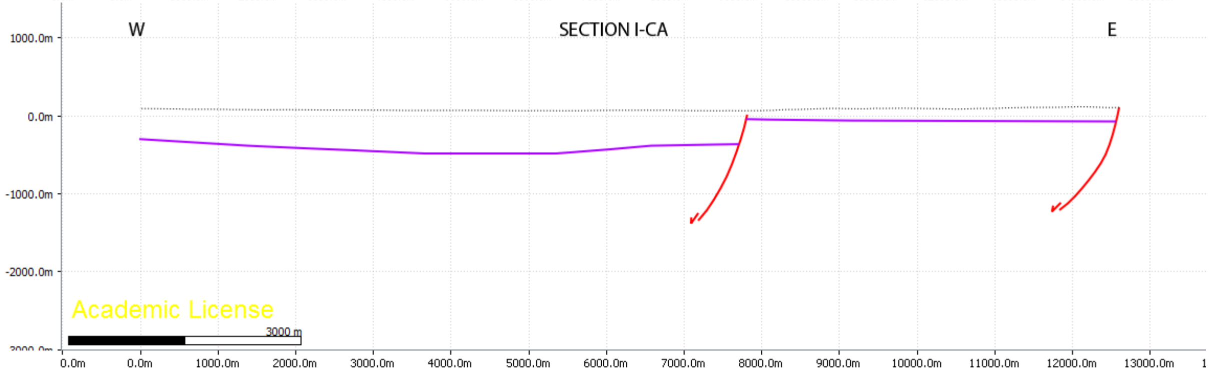
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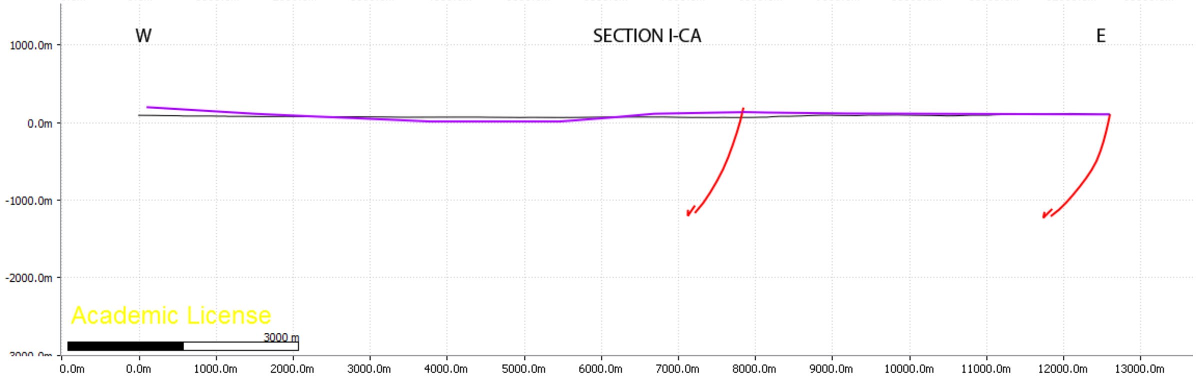
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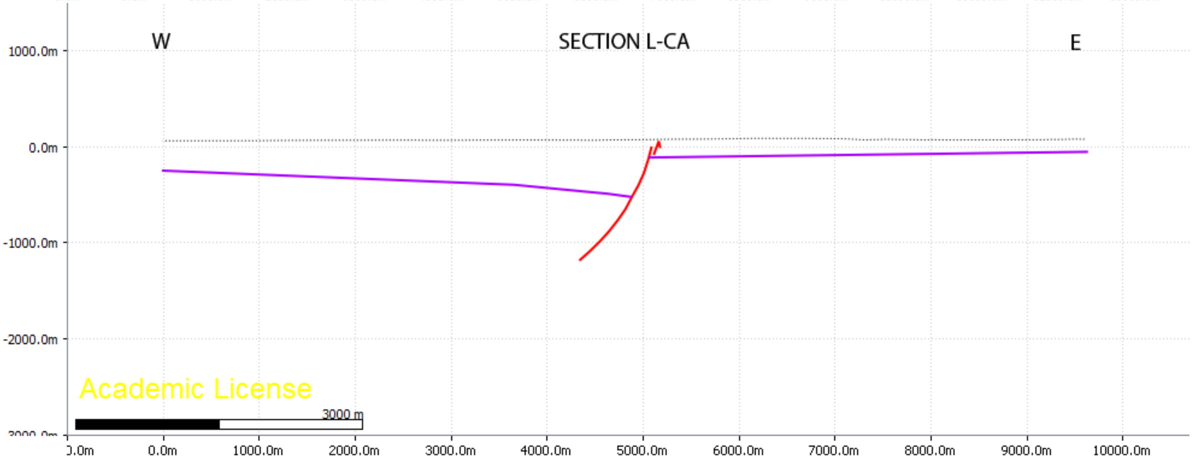
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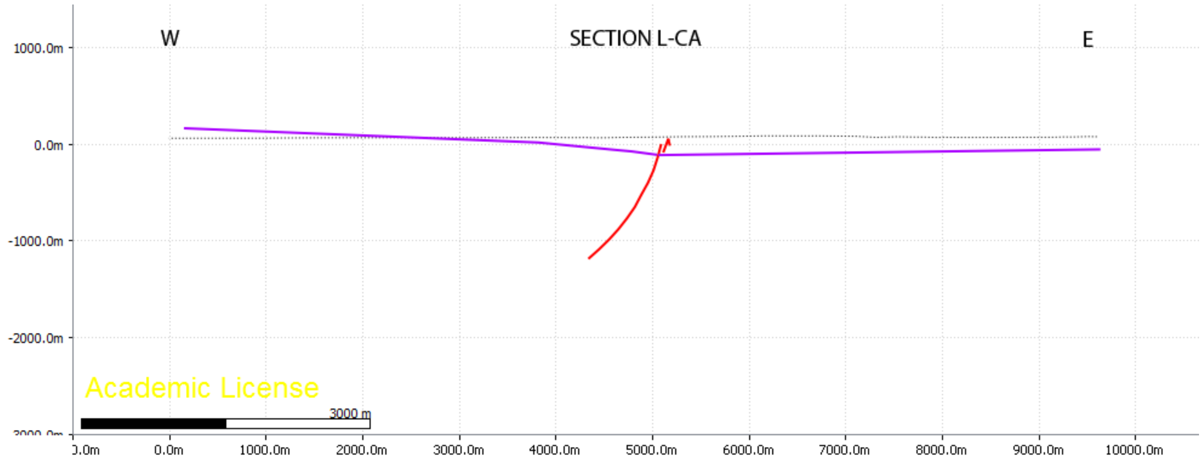


Fig.3.4.3- Deformed and restored cross-sections achieved from the 3D model of the Middle Pliocene erosional surface (purple) in the northern and southern Campidano. The location map of the cross-section is in Fig.3.4.1.

fault in the eastern edge that affected the Gesturi marls and the Oligo-Miocene volcanics are Plio-Pleistocene in age. With the same principle, the fault in the eastern edge that displaces down the Middle Pliocene erosional surface was not restored moving it to the topographic surface, but restoring the top of the acoustic basement detected in both the hangingwall and footwall sides of the fault. Furthermore, this cross-section shows a fault that was surely active only in Miocene times, because sealed by the Samassi formation and another that was not surely active during Miocene because, restoring the Middle Pliocene erosional surface, the deformation affecting the top of the acoustic basement and the base of the Gesturi marls is perfectly restored too. Furthermore, from this cross-section is possible to note that, if the Middle Pliocene erosional surface is restored to the horizontal, this operation coerces distortions in the underlying succession, generating unrealistic geometries (Fig.3.4.5). This demonstrates that the shape of the erosional surface is not due to the deformation affecting the

Section	Trend (°)	L_1 (m)	L_0 (m)	ΔL (m)	e (%)	β
A-Ca	060	10,495	10,018	477	4.76	1.05
B-Ca	060	10,725	10,158	567	5.58	1.06
C-Ca	060	11,009	10,413	596	5.72	1.06
C1-Ca	062	14,786	13,785	1,001	7.26	1.07
D-Ca	060	11,422	10.983	439	4.00	1.04
E-Ca	060	11,601	11,250	351	3.12	1.03
F-Ca	060	11,991	11,688	303	2.59	1.03

G-Ca	060	13,841	13,290	551	4.15	1.04
H-Ca	088	14,571	14,087	484	3.44	1.03
I-Ca	090	12,627	12,422	205	1.65	1.02
L-Ca	089	9,671	9,389	282	3.00	1.03
A-Or	090	16,858	16,508	350	2.12	1.02
B-Or	090	17,306	16,938	368	2.17	1.02
C-Or	090	20,600	20,429	171	0.84	1.01
D-Or	089	22,716	22,251	465	2.09	1.02
E-Or	089	20,778	20,598	180	0.87	1.01
F-Or	090	15,607	15,226	381	2.50	1.02

Tab.3.1– The extension values (ΔL), achieved from the difference between the deformed initial lenght (L_1) and the restored final lenght (L_0), the elongation (e) and the extension factors (β) estimated for every cross section carried out.

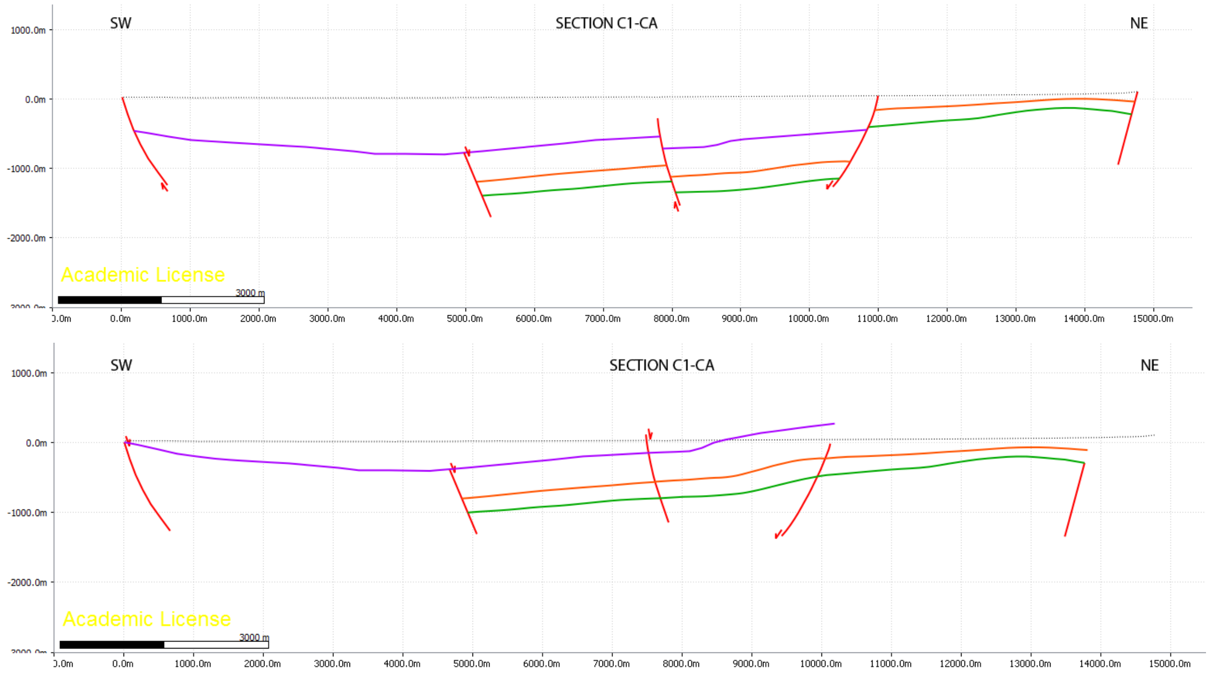


Fig.3.4.4- Deformed and restored cross-section C1-Ca in the southern Ca. Purple: Middle Pliocene erosional surface; orange: bottom of the Gesturi marls; green: top of the acoustic basement. The location of the cross-section is in Fig.3.4.1.

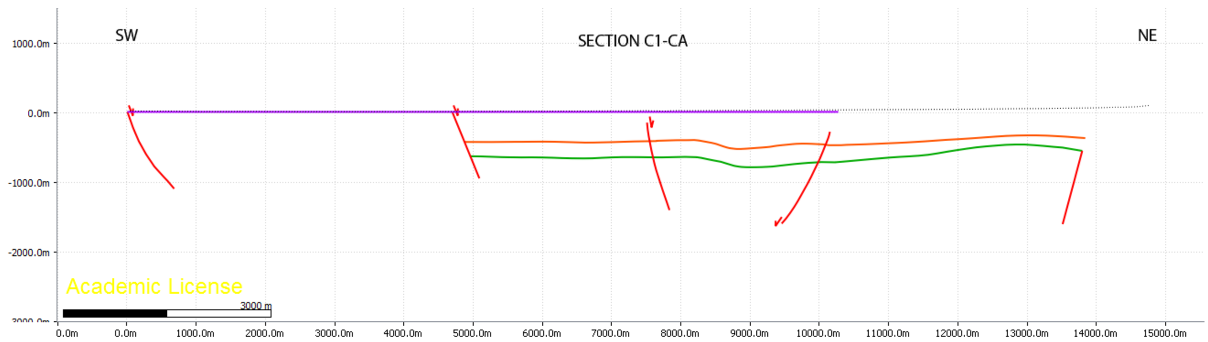


Fig.3.4.5- Restored C1-Ca cross-section showing that restoring to the horizontal the Middle Pliocene erosional surface (purple), unrealistic geometries are generated in the Miocene underlying succession.

hangingwall during the fault activity, but is the original shape of the paleotopography. On the other hand, in the seismic lines and in the two way time structural map, deformation due to the faulting affecting the Middle Pliocene erosional surface occurs, as for example the gentle rollover anticline. Therefore, it is difficult discern when the shape of the erosional surface is related to the paleotopography or to the deformation. Generally, if the lines had been straightened, the measured extension value would decreases. Nevertheless, in this case, if the erosional surface is straightened or not, the calculated extension values do not show important differences.

3.4.2 Plio-Pleistocene extension rate

Once that extension is measured, knowing the time range in which it occurred, the extension rate can be calculated. As mentioned before, the lower time-marker considered in the restored cross-sections is the erosional surface at the base of the Samassi formation, that is dated at 3.5 Ma. Unfortunately, there is not a upper time-marker, thus it is no possible to directly estimate the extension rates. To approximate a upper time-marker to achieve the time range to which refer the extensional tectonics, the vertical slip rate affecting the Samassi formation, where its top can be dated, can be used.

In the northern Campidano, the line 2 shows close to the master fault a 600 m thick succession of Samassi formation, sealed by interpreted basalt lava-flows (Fig.3.4.6). The basalts have not continuity in the seismic lines, but those in the line 2 can be correlated with those in the Oristano1 well, where the core extract just below the basalts is basal Pleistocene in age. Thus, for the basalts detected in the line 2 an age of 2.5 Ma can be assigned, which is in agreement with those attributed to the basalt-lava flows cropping out to the east, in particular in the Monte Arci and "Giara di Gesturi". This means that a vertical slip rate of 0.6 mm/yr for the Samassi formation in this point, referred to the master fault, can be calculated. Here, the erosional surface reaches 1,040 m below the sea level. In fact, also the basalts are displaced with a throw of 440 m, proving that tectonics continued to be active in the Pleistocene times too.

The vertical slip rate of the basalts displacement can not be carefully evaluated, because there are not a younger time marker. Assuming that the vertical slip rate is equal to those previously calculated for the Samassi formation, 0.6 mm/yr, to get a throw of 440 m 0.73 Ma are required. From the basalts time-marker of 2.5 Ma, therefore, it can be assumed that the tectonics continues for other 0.73 Ma, that is up to 1.77 Ma (Calabrian). Finally, 1.77 Ma can be considered the upper time-marker searched to achieve the time range to which refer the extensional tectonics and to calculate the extension rate. Supposing therefore that the extensional tectonics is referred to a range of time of 1.73 Ma (between 3.5 Ma and 1.77 Ma), and considering the maximum extension value achieved from the restored cross-sections in the northern Campidano, that is 465 m, the extension rate is 0.3 mm/yr.

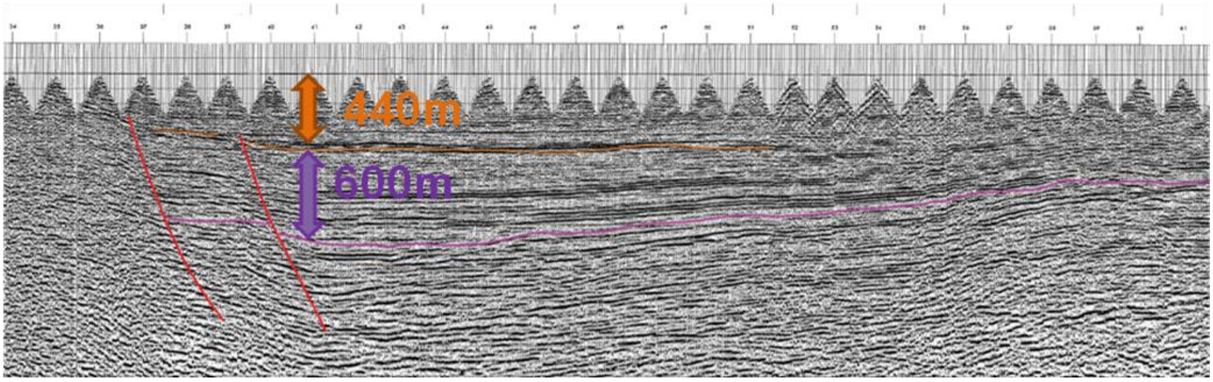


Fig.3.4.6- Seismic line 2, in the northern Campidano, showing the time-markes of 3.5 Ma (purple: erosional surface) and 2.5 Ma (brown: basalts) and the thickness of the successions.

In the southern Campidano, to determine the age of the erosional surface at the base of the Samassi formation is more difficult, because the Lower Pliocene is missing and the Samassi formation lies above the Upper Miocene succession, in the Campidano 1 well, or the Gesturi marls, as well as directly above the acoustic basement. So, the age of this surface could be also significantly older than the Middle Pliocene. However, the faunas characterizing the Lower Pliocene, that are *Globorotalia margaritae* and *Globorotalia puncticulata*, have been found reworked in the Samassi formation (PECORINI & POMESANO CHERCHI, 1969). This could mean that the Nuraghe Baboe Formation (Lower Pliocene), cropping out in the Sinis peninsula and crossed by the Oristano 1 well, were deposited in the southern Campidano too, but has not been preserved, not even in subsurface. Therefore, if in the southern Campidano the Nuraghe Baboe Formation has been eroded, an uplift of that area must be admitted before the deposition of the Samassi formation and its basal erosional surface should be younger in the southern than in the northern Campidano. As a consequence, the lower time-marker of the tectonics in the southern Campidano should be younger than in the northern.

To try to assign an age more precise to the erosional surface at the base of the Samassi formation in the southern Campidano, the vertical slip rate achieved from the data in the northern Campidano and the limit of the basal Pleistocene in the southern Campidano have been used. A basal limit Pleistocene in age has been identified in seismic lines from the electric logs of the Campidano 1 well, although in the southern Campidano no Plio-Quaternary basalts occur in the subsurface and only small outcrops have been detected in the sourrounding areas. In the line CA-303-92-V, that is the line where the role of the western master fault is better shown, the succession between the basal limit Pleistocene and the erosional surface at the base of the Samassi formation is 240 m thick (Fig.3.4.7). Considering the same vertical slip rate for the Samassi formation (0.6 mm/yr) in the northern Campidano, this succession should be deposited during 0.4 Ma. The age of the erosional surface at the base of the Samassi formation, then, can be dated at 2.9 Ma, considering the basal limit Pleistocene at 2.5 Ma and adding to it 0.4 Ma that is the estimated time of deposition of the Samassi formation in that area. The basal Pleistocene limit at 2.5 Ma, instead, occur at 600 m below the sea level and, then, this succession should be deposited during 1 Ma considering always the same vertical slip rate (0.6 mm/yr). Therefore, the basal limit Pleistocene at 2.5 Ma was displaced up to -600 m during 1 Ma and this allows to hypotize that the tectonics ended at 1.5 Ma (Calabrian). Finally, the time range to which refer the extensional tectonics in the southern Campidano is 1.4 Ma (between 2.9 Ma and 1.5 Ma). Considering the maximum extension value measured in the restored cross-sections, that is 596 m, the extension rate in the southern Campidano is 0,4 mm/yr.

It is not ignored that the extensional rate calculated in this way for the southern Campidano based on the evolution recognized in the northern sector, suffered of several hypothetical assumptions and looks too similar to a cyclic reasoning. Anyway the obtained value is not so different from the northern Campidano and can be considered acceptable.

Actually, the vertical slip rate and the extensional rates calculated for the northern and southern Campidano are normal values in comparison with other studied half-graben (0.04 mm/yr to 0.3 mm/yr in the Maestrat grabens (eastern Spain) (SIMÓN *et alii*, 2013); 0.4 mm/yr to 6.7 mm/yr in the Gulf of Corinth (BELL *et alii*, 2008); 0.23 mm/yr in the Lower Rhine Graben and 0.32 mm/yr in the Swabian Jura zone (AHORNER, 1975); 0.1 mm/yr to 0.5 mm/yr in the Hatay graben (southern Turkey) (BOULTON & WHITTAKER, 2009); 0.5 mm/yr to 2.1 mm/yr in the Baikal rift (southeastern Russia) (SAN'KOV *et alii* 2000), where the time-markers to calculate the rates of deformation are better constrained. Thus, the values achieved corroborate also the approximations that had necessarily to be made to define the time-markers in the Campidano.

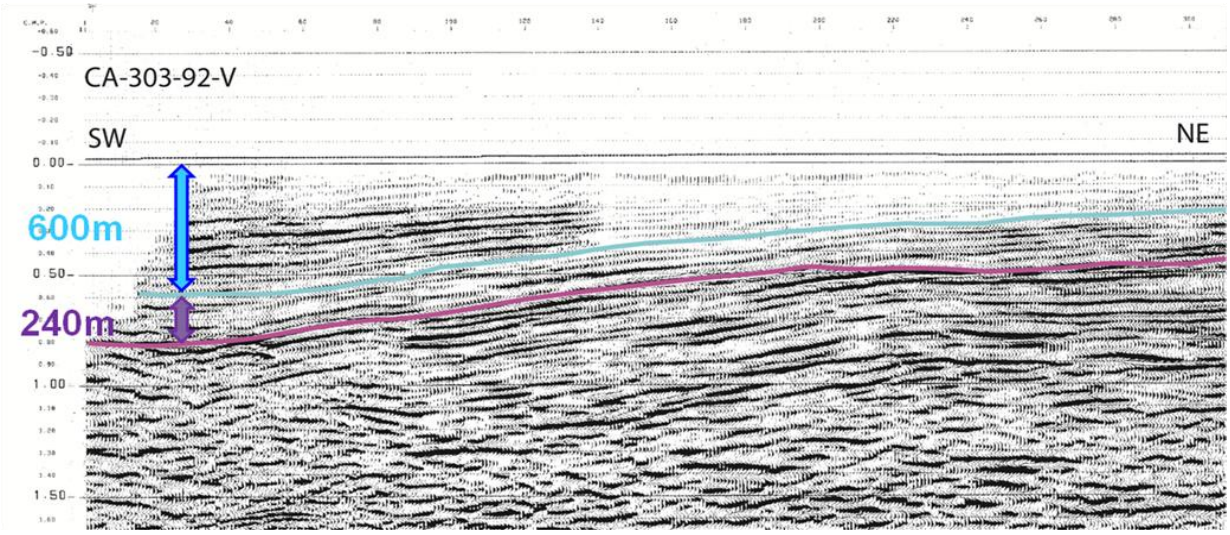


Fig.3.4.7- Seismic line CA-303-92-V, in the southern Campidano, showing the time-markes of 3.5 Ma (purple: erosional surface) and 2.5 Ma (brown: basal Pleistocene) and the thickness of the successions.

3.5 PALEOSTRESS RECONSTRUCTION IN THE CAMPIDANO AREA DURING PLIO-PLEISTOCENE TIMES

To reconstruct the paleostress field, it is necessary to know the strike and dip of the fault planes and the movement direction on the fault planes at that time. Concerning the paleostress field active in the Campidano area during Plio-Pleistocene times, faults are poorly preserved, and on exposed fault mirrors generally there are not kinematic indicators. The rare kinematic indicators observed (i.e. along the "Soglia di Siliqua") can not unambiguously referred to Pliocene time, but are generally easier ascribable to Oligo-Miocene tectonics (see chapter 1). Thus, the geometry of the fault planes and the related slickensides are not detectable.

From the built 3D model of the Middle Pliocene erosional surface at the base of the Samassi formation and the normal faults that affect it, the geometry of the fault planes is now well known, but not the movement direction on them. A method to know indirectly the movement direction on the fault planes is the restoration of the displaced surfaces. The method chosen to restore the 3D surface is that from ROUBY *et alii* (2000), because it allows the restoration of complex fault patterns and obtain the direction of slip on faults. The principle of the restoration method is shown in Fig.3.5.1.

The initial data are stratigraphic horizons represented by triangulated surfaces (surfaces composed of triangular elements) offset by the faults (Fig.3.5.1a). First the horizons are unfolded (Fig.3.5.1b) and, after unfolding, unfaulting is performed in map view. Before unfaulting, a volume of rocks affected by normal faults appears as gaps (black area in Fig.3.5.1b) separating fault compartments (Fig.3.5.1b) (reverse faults appear as overlaps between fault blocks). To invert the displacement on the faults, the fault gaps are closed by rigid-body motion of the fault compartments (Fig.3.5.1c). The difference between the deformed and the restored state gives the 3D finite displacement field and the directions of slip on the faults (Fig.3.5.1d).

In the model proposed by Rouby *et alii* (2000) the unfolding step is required because fold are related to fault movement (hangingwall rollover anticlines).

Concerning the restoration of the Middle Pliocene erosional surface, the unfolding step is not required because the shape of the surface is due mainly to its paleotopography. Actually, no important dissimilarities occur in map view between the modelled surface and the flattened surface. Thus, the unfaulting step can be directly applied. The method used to unfaulting

(ROUBY *et alii*, 1993; 1996a; 1996b; 2000; ROUBY and COBBOLD, 1996) removes the displacement on the faults in map view and assumes that the fault displacement is achieved by rigid-body motion of the fault blocks (Fig.3.5.2).

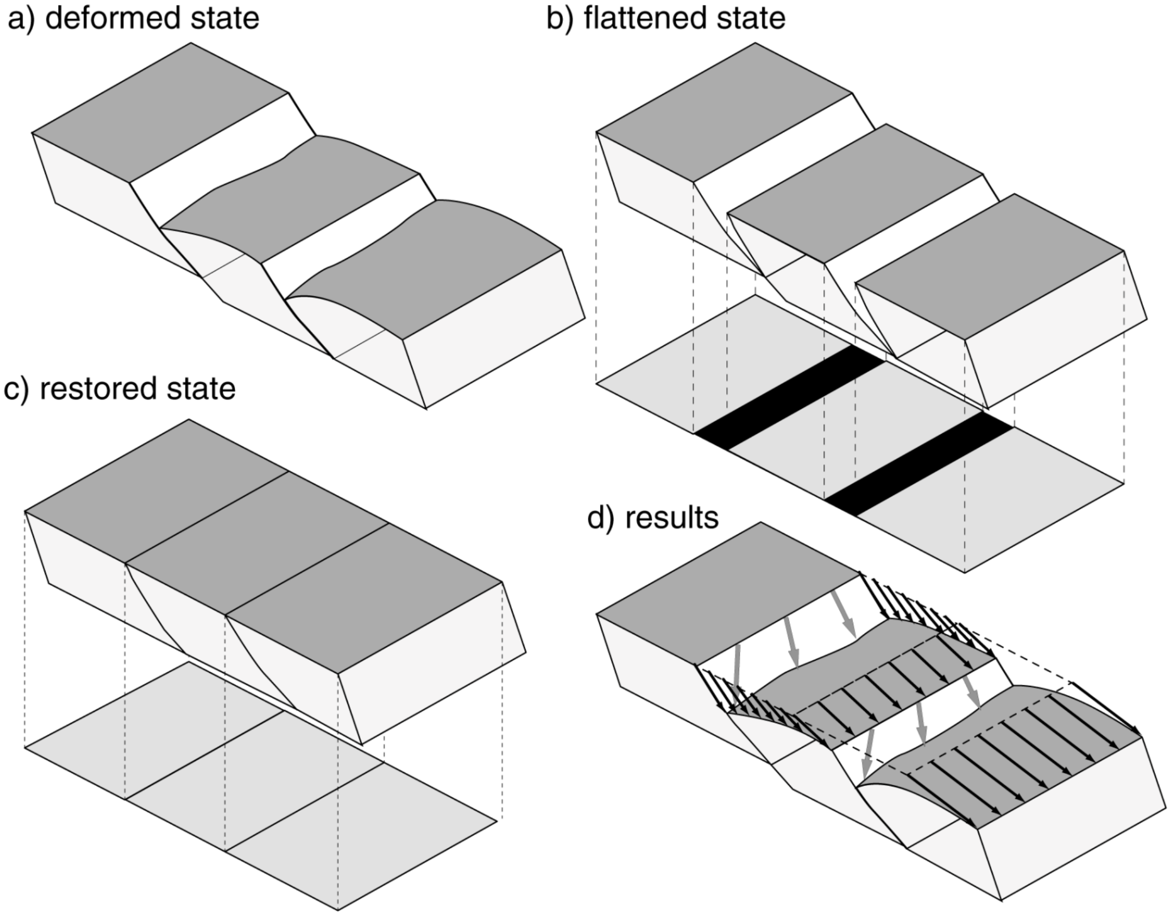


Fig.3.5.1- Principle of the restoration method of normal fault (after ROUBY *et alii*, 2000). Gray arrows: slip direction; black arrows: finite displacement. See text for explanation.

From the fault heave map (Fig.3.5.2a), a mosaic of fault-bounded blocks is built (Fig.3.5.2b) by extrapolating fault traces and adding artificial block boundary, separated by gaps representing the normal faults (Fig.3.5.2c). It is assumed that the fault displacement is restored when these gaps are closed. The blocks are therefore sequentially packed against a stationary block (in gray in Fig.3.5.2c and 3.5.2d) using rigid-body rotations and traslations to minimize gaps and overlaps (Fig.3.5.2d). The difference between the faulted and restored surfaces gives the faulting vectors (Fig.3.5.2e).

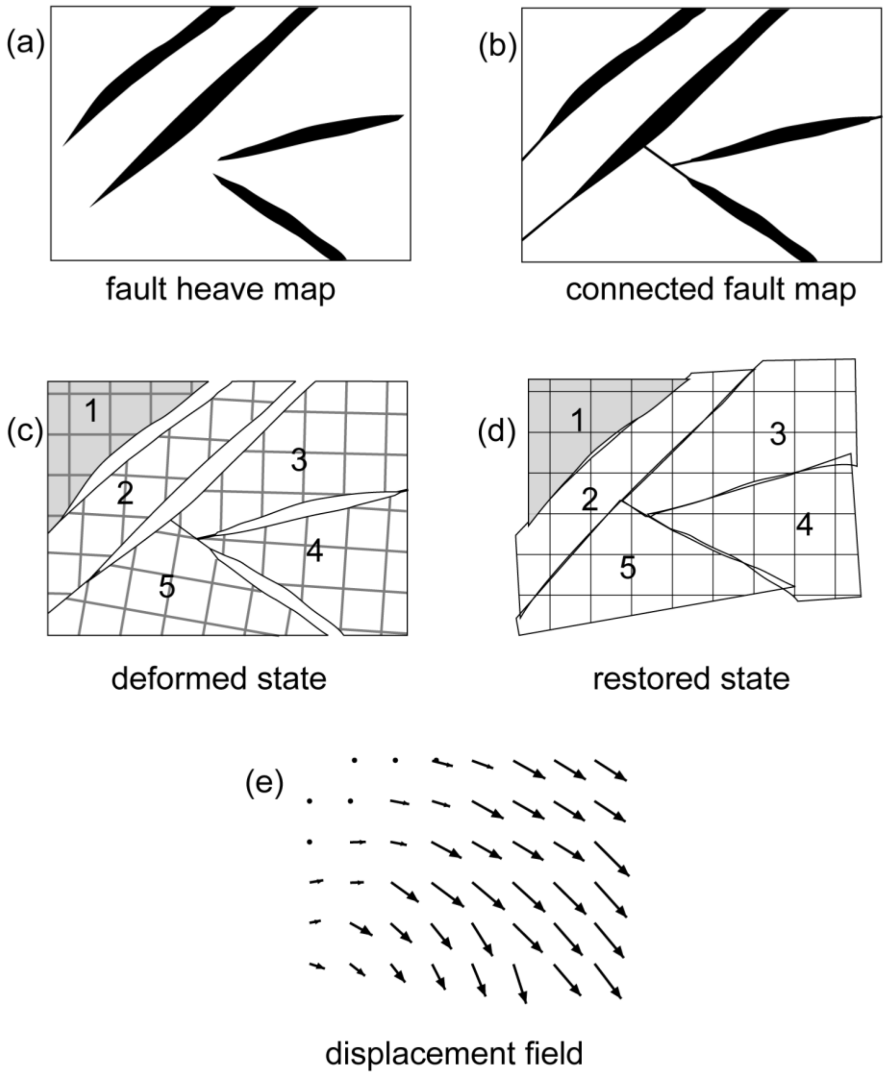
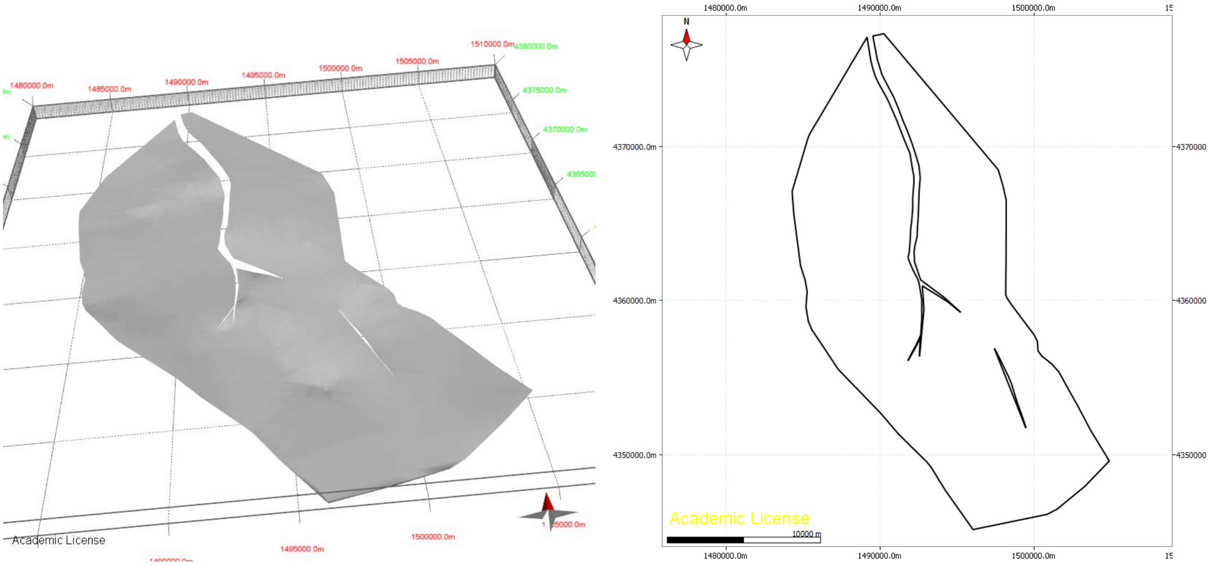


Fig.3.5.2- Principle of the unfaulting step (after Rouby *et alii*, 1996a). See text for explanation.

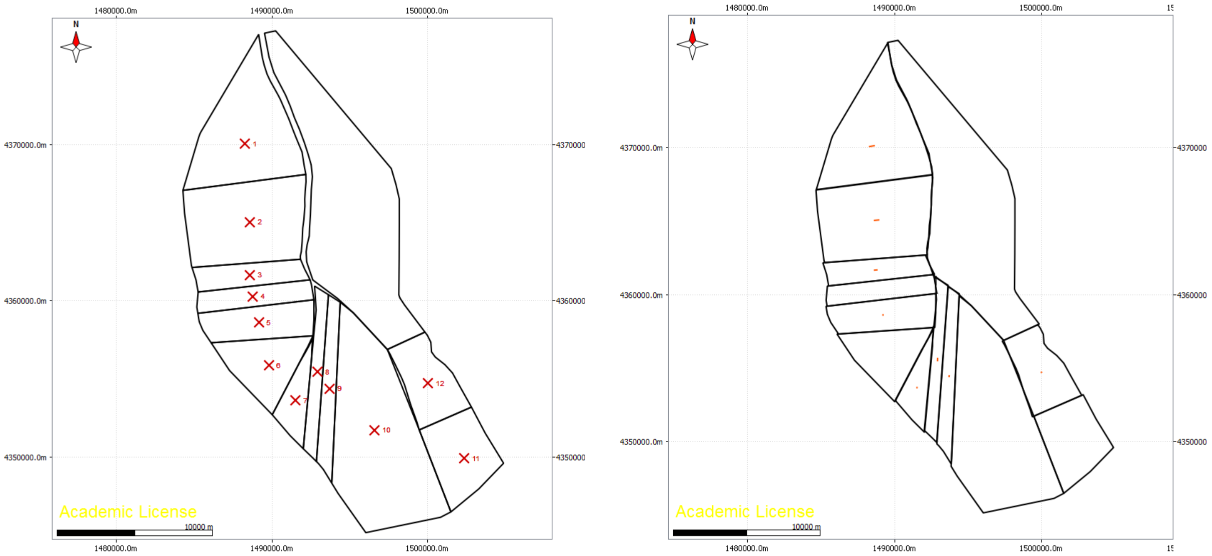
The restoration, using the method described above, of the Middle Pliocene erosional surface in both the northern and southern Campidano has been carried out using MOVE. First of all, in map view, the surfaces have been split to create several blocks. Once that the fault-bounded block map has been built, a point of reference has been drawn in every rigid block. Before moving the rigid block for the restoration, the block map is duplicated. The duplicated block map was then restored packing the different blocks and minimizing the gaps and overlaps. Once that the restored block map is overlapping to the deformed block map, the movement vectors of the blocks are obtained joining the reference points in the deformed state with those in the restored state.

The restoration workflow in the southern Campidano is shown in Fig.3.5.3. Here, the rigid block restoration did not allow to obtain the slip vectors in the western and eastern edge faults, because the Middle Pliocene erosional surface is missing in the footwall.



a) 3D view

b) Map view

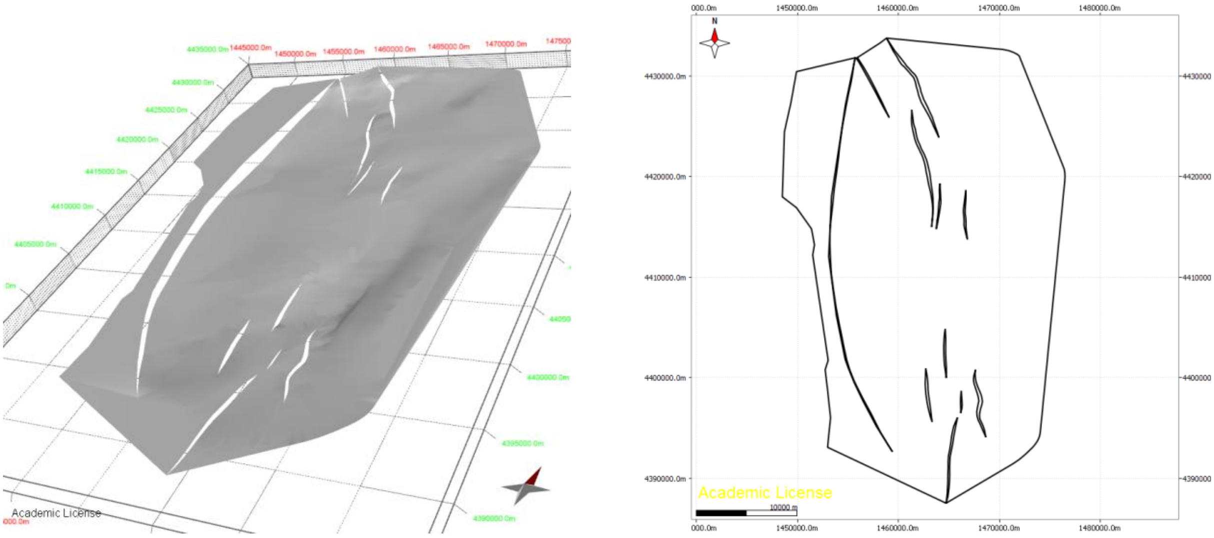


c) Rigid blocks map

d) Restored state

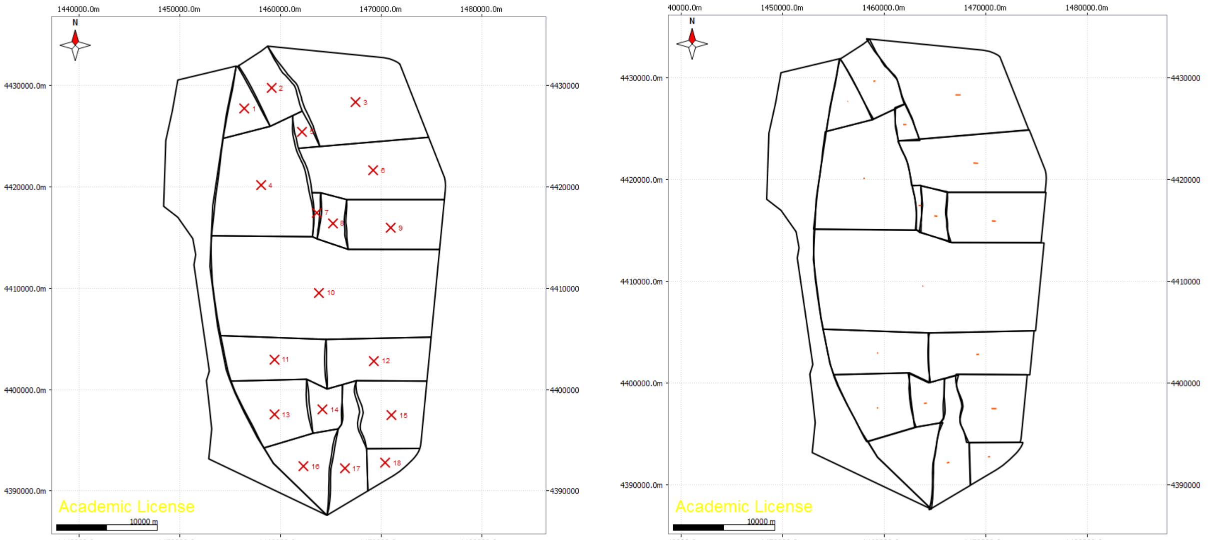
Fig.3.5.3- Rigid block restoration workflow in the southern Campidano. The 3D surface (a) in map view (b) is split in several blocks (c) that are packing against the northeastern rigid block (d). The red X (c) are the reference points. The orange segments (d) represent the movement vectors.

With the same principle and processes, the Middle Pliocene erosional surface in the northern Campidano is also restored (Fig.3.5.4).



a) 3D view

b) Map view



c) Rigid blocks map

d) Restored state

Fig.3.5.4- Rigid block restoration workflow in the northern Campidano. The 3D surface (a) in map view (b) is split in several blocks (c) that are packing against the western rigid block (d). The red X (c) are the reference points. The orange segments (d) represent the movement vectors.

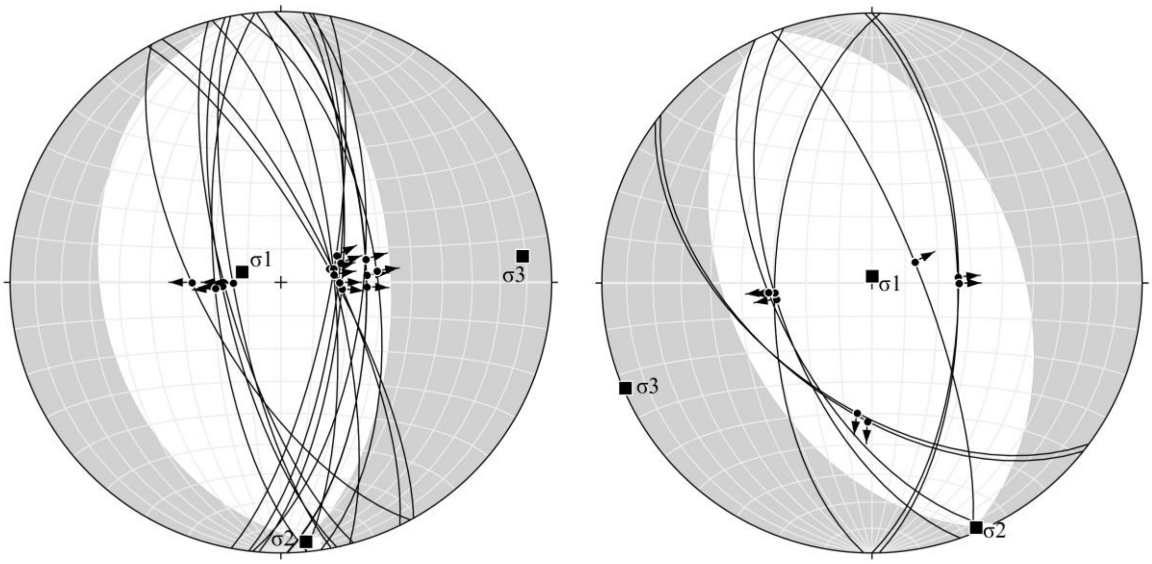
To achieve the slip vectors on the fault planes, the horizontal vectors of the movement of the rigid blocks obtained with the restoration have to be projected on the fault planes. The plunge and trend of the slip vectors are then achieved, using a stereoplot, from the intersection of the vertical planes containing the horizontal vectors of the movement of the rigid blocks and the fault planes on which the blocks are restored.

The fault slip data so obtained are imported into FaultKin5.2 software by R. Allmendinger. This software allows to plot the data and calculate, using the right dihedra method of fault slip inversion, the principal stress axes.

In the northern Campidano, the result show an extension oriented roughly E-W, with the principal stress axes: $\sigma_1=285/78$ $\sigma_2=175/4$ $\sigma_3=84/11$ (Fig.3.5.5a).

In the southern Campidano, the result show an extension oriented roughly ENE-WSW, with the principal stress axes: $\sigma_1=357/88$ $\sigma_2=157/2$ $\sigma_3=247/1$ (Fig.3.5.5b).

To corroborate the paleostress field data obtained with the method described above, that, although carried out using a computer, is a manual method, the slip vectors on the fault planes have been calculated also using the "Geomechanical Modelling" module available in MOVE.



a) Northern Campidano

b) Southern Campidano

Fig.3.5.5- Fault slip data and principal stress axes obtained using the rigid block restoration method in map view. Equivalent projectionon lower emisphere. Data have been elaborated with FaultKin5.2 by Allmendinger.

To restore deformed and complexly faulted surfaces, Geomechanical Modelling uses a mass-spring approach, an iterative energy minimization technique that aims to preserve the original shape of a surface or volume. The workflow allows for heterogeneous (non-plane strain) displacements based on physical laws of motion. The module also allows for a maintained area or volume and minimizes strain. Once that the surface has been restored, it is possible to capture attributes such as the horizontal displacement, that, as in the rigid blocks restoration in map view, is used to calculate the slip vectors on the fault planes.

The workflow to restored the Middle Pliocene erosional surface in both the southern and northern Campidano using Geomechanical Modelling is show in Fig.3.5.6 and Fig.3.5.7 respectively.

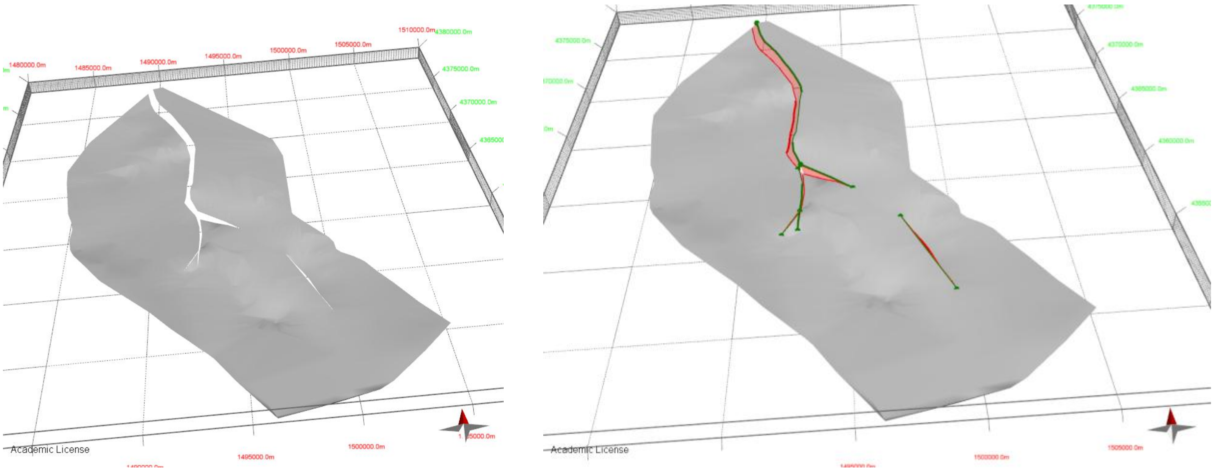
Starting from the faulted 3D surfaces (Fig.3.5.6a and Fig.3.5.7a), the set of fault cut-off constraints have been specified. Fault cut-off constraints allow the user to decide which fault gaps will be closed in the restoration. Cut-off constraints are shown as red surfaces between the fault cut-offs, which are shown as red (hangingwall cut-offs) and green (footwall cut-offs) lines in the view (Fig.3.5.6b and Fig.3.5.7b). Once that the restoration ended (Fig.3.5.6c and Fig.3.5.7c), the horizontal displacement attribute can be visualised in the 3D view (Fig.3.5.6d and Fig.3.5.7d). The colour maps show the areas of the surfaces where the deformation is high (purple) or low (blue). Clearly, the important horizontal displacement vectors are those that lie on the faults gaps, because are the movement vectors of the rejoined points in the hangingwall and in the footwall cut-off lines, and are those that, projected on the fault planes, allow to achieved the slip vectors.

Then, using the same method described for the slip vectors obained with the rigid block restoration, the principal stress axes were calculated.

In the northern Campidano, the result show an extension oriented roughly E-W, with the principal stress axes: σ_1=263/77 σ_2=356/1 σ_3=86/13 (Fig3.5.8a).

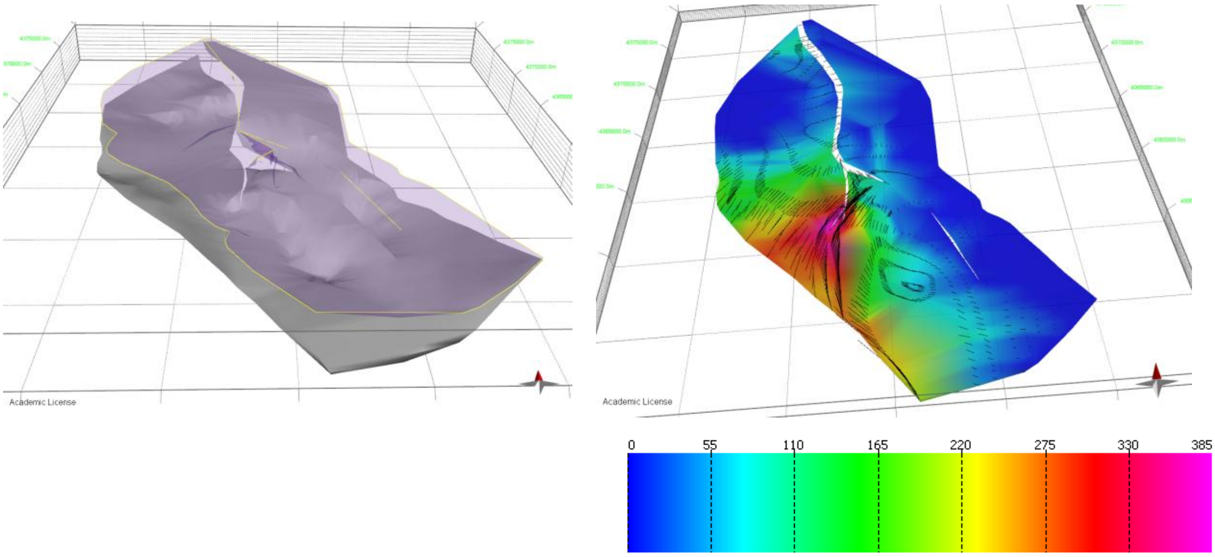
In the southern Campidano, the result show an extension oriented roughly ENE-WSW, with the principal stress axes: σ_1=105/85 σ_2=332/3 σ_3=242/3 (Fig.3.5.8b).

The results on the calculated paleostress fields are corroborated by the fact that no important differences occur in the paleostress fields calculated using the two different methods.



a) 3D surface

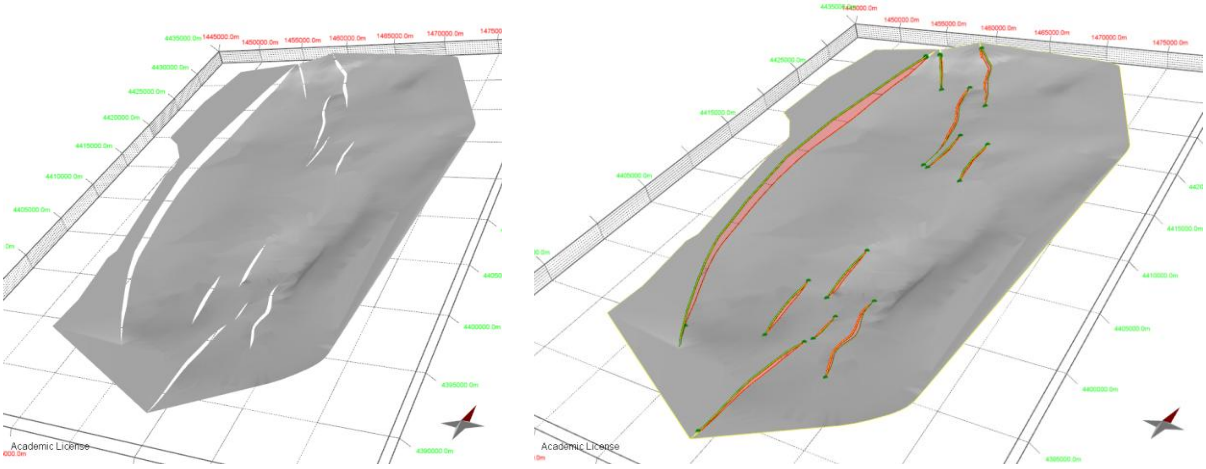
b) Cut-off constraints



c) Restored surface (transparent purple)

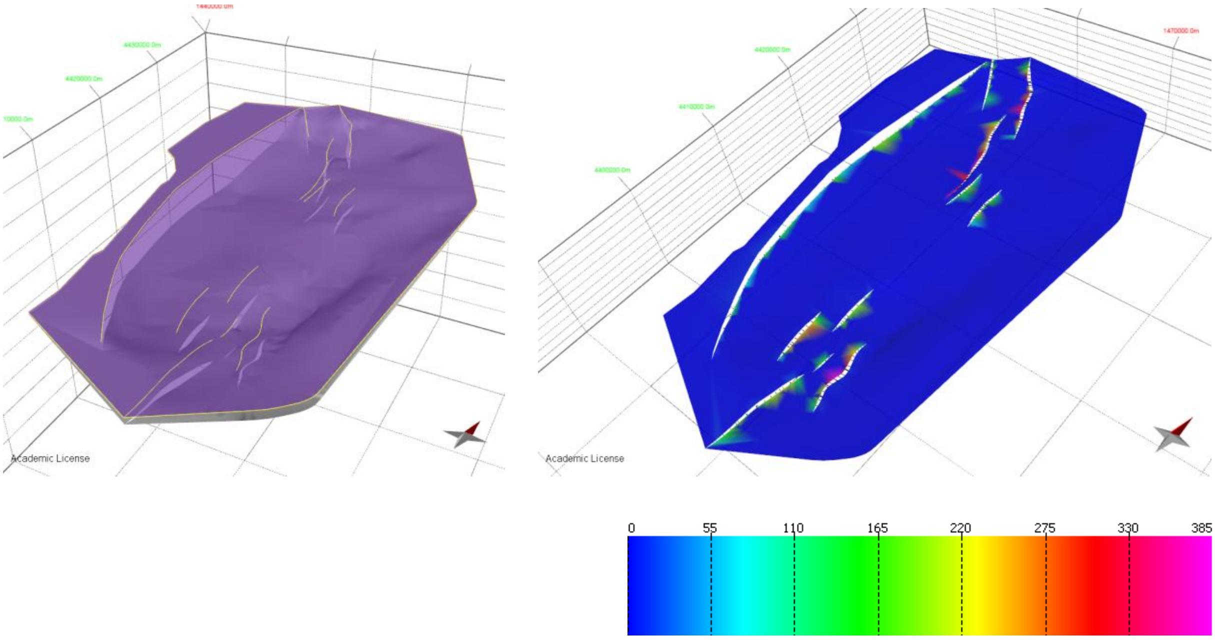
d) Horizontal displacement attribute

Fig.3.5.6- "Geomechanical Modelling" (module from MOVE) restoration workflow of the Middle Pliocene erosional surface in the southern Campidano.



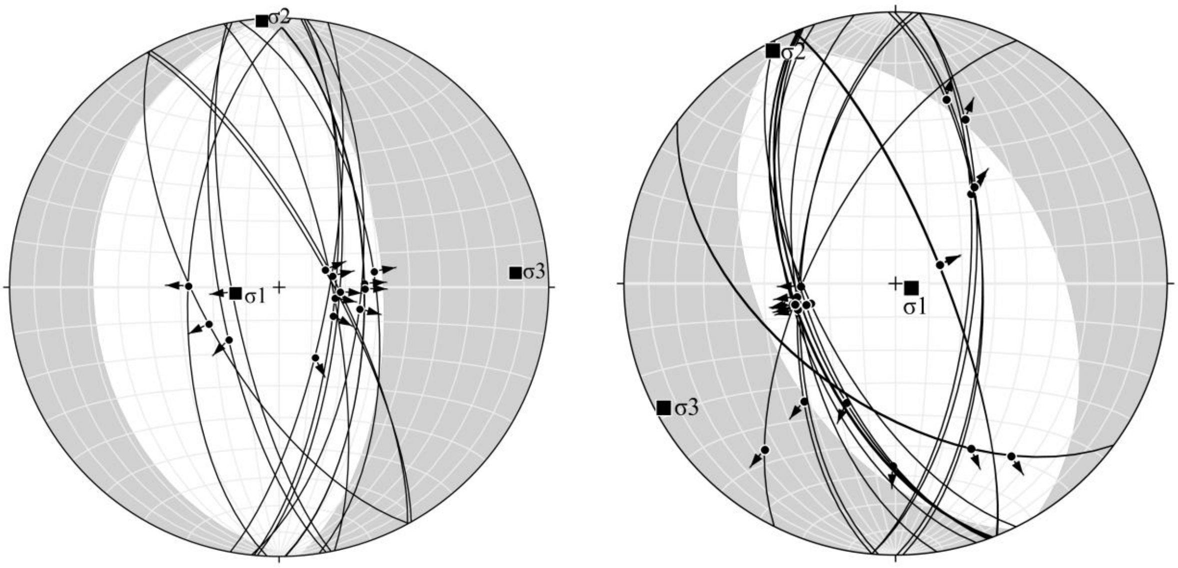
a) 3D surface

b) Cut-off constraints



c) Restored surface (transparent purple)
d) Horizontal displacement attribute

Fig.3.5.7- Geomechanical Modelling restoration workflow of the Middle Pliocene erosional surface in the northern Campidano.



a) Northern Campidano
b) Southern Campidano

Fig.3.5.8- Fault slip data and principal stress axes obtained using the Geomechanical modelling restoration method.

4 DISCUSSIONS

The results shown in the previous chapter are here critically discussed and evaluated, showing how they agree or contrast with published works and how they can be useful to better define the geodynamic context of the tectonic evolution of the southern Sardinia in the last million years.

The chapter is organized into three specific subsections, each dealing with a different subject: some observations on the Oligo-Miocene evolution of Sardinia; the discussion of the calculated extension values and paleostress fields related to the Plio-Pleistocene evolution of southern Sardinia; the geodynamic context to the which the Plio-Pleistocene deformations in southern Sardinia are related.

4.1- SOME CONSIDERATIONS ON THE OLIGO-MIOCENE EVOLUTION OF SOUTHERN SARDINIA

Although the focus of the research concerns the Plio-Pleistocene evolution of southern Sardinia, during the interpretation of the electric logs and seismic lines some observations have been made on the stratigraphic and tectonic setting during Oligo-Miocene times.

The first consideration, based on the elctric logs interpretation, concern the Miocene stratigraphic succession. In fact, how alredy said in the chapter 1, the majority of the Authors agree with the separation of the Miocene sedimentary succession into three cycles (ASSORGIA *et alii*, 1997; CARMIGNANI *et alii*, 2001, 2004, and references therein): the 1° Miocene cycle is Upper Oligocene-Lower Burdigalian in age, the 2° Miocene cycle is Upper Burdigalian-Langhian in age and the 3° Miocene cycle is Serravalian-Tortonian-?Messinian in age.

The interpretation of the spontaneous potential and resistivity logs in the Marcella, Campidano1 and Oristano1 wells, that cross entirely the Miocene succession (Oristano2 well cross only the upper part of the Miocene succession), does not confirm the existence of a boundary between the 1° and 2° Miocene cycles, but, they could be considered a single depositional sequence. It seems, in fact, that the boundary between the 1° and 2° Miocene cycle coincides with a maximum flooding surface. According this interpretation from electric logs, this maximum flooding surface separates the transgressive system track, that coincides with the 1° Miocene cycle, from the regressive system track, that coincides with the 2° Miocene cycle.

Otherways, in outcrops in the Trexenta-Sarcidano area, the boundary between the 1° and 2° Miocenic cycles is characterized by a low angle angular unconformity, and, sometimes, for the occurrence of conglomerates (FUNEDDA *et alii*, 2012).

This different interpretation arise also from the seismic line ES-319, in the Cagliari Gulf, where an angular unconformity is interpreted as the boundary between the 1° and 2° cycles, particularly clear between the shot points 149 and 83 (Fig.4.1A).

The data from well-logs seem to be in contradiction with those shown from seismic lines and outcrops. This can be due to the fact that the sedimentation was controlled not only by the changes in the sea level, but also by tectonics. Thus, while erosion occurred in an area in other sectors the sedimentation could be continuous. This can then explain why the sedimentation is conformable in some areas and in others an erosional surface, more or less marked, occur. A strong angular unconformity of Burdigalian age has been described in northern Sardinia by OGGIANO *et alii* (1995) and FUNEDDA *et alii* (2000) that ascribed it to a general regional change in the tectonic environment, coeval to the opening of Algero-Provençal basin and following the end of closure of the Liguro-Piemont ocean.

However, other Authors interpreted differently this seismic line.

According to CASULA *et alii* (2001), the unconformity is the boundary between the sequence B2, that coincides with the upper part of the 1° Miocene cycle, and the sequence C, that coincides with the 2° Miocene cycle. Thus, the stratigraphic interpretation concerning the uncorfomity is almost the same proposed in this research, although they mapped it differently. The difference between our interpretation and that of CASULA *et alii* (2001) arises in the occurrence, according to these Authors, of the sequence D, that coincides with the Lower Pliocene marine succession marked at the base by the Messinian erosion, lying above the sequence C (Fig.4.1B). In this research, the sedimentary succession between the Middle Miocene unconformity and that at the base of the Samassi formation is ascribed entirely to the Upper Burdigalian-Langhian.

Completely different is, instead, the interpretation made by FINETTI *et alii* (2005). In fact, the angular unconformity interpreted as occurred in Middle Miocene according this research and CASULA *et alii* (2001), by FINETTI *et alii* (2005) is interpreted as the Messinian erosional unconformity and, consequently, the overlying sedimentary successions is totally ascribed to the Pliocene and Quaternary deposits (Fig.4.2). Actually, a similar strong erosion looks ascribable to the important sea level fall related to the Messinian salinity crisis. But this interpretation is not verified by transfering the stratigraphic log of Marcella well with loop

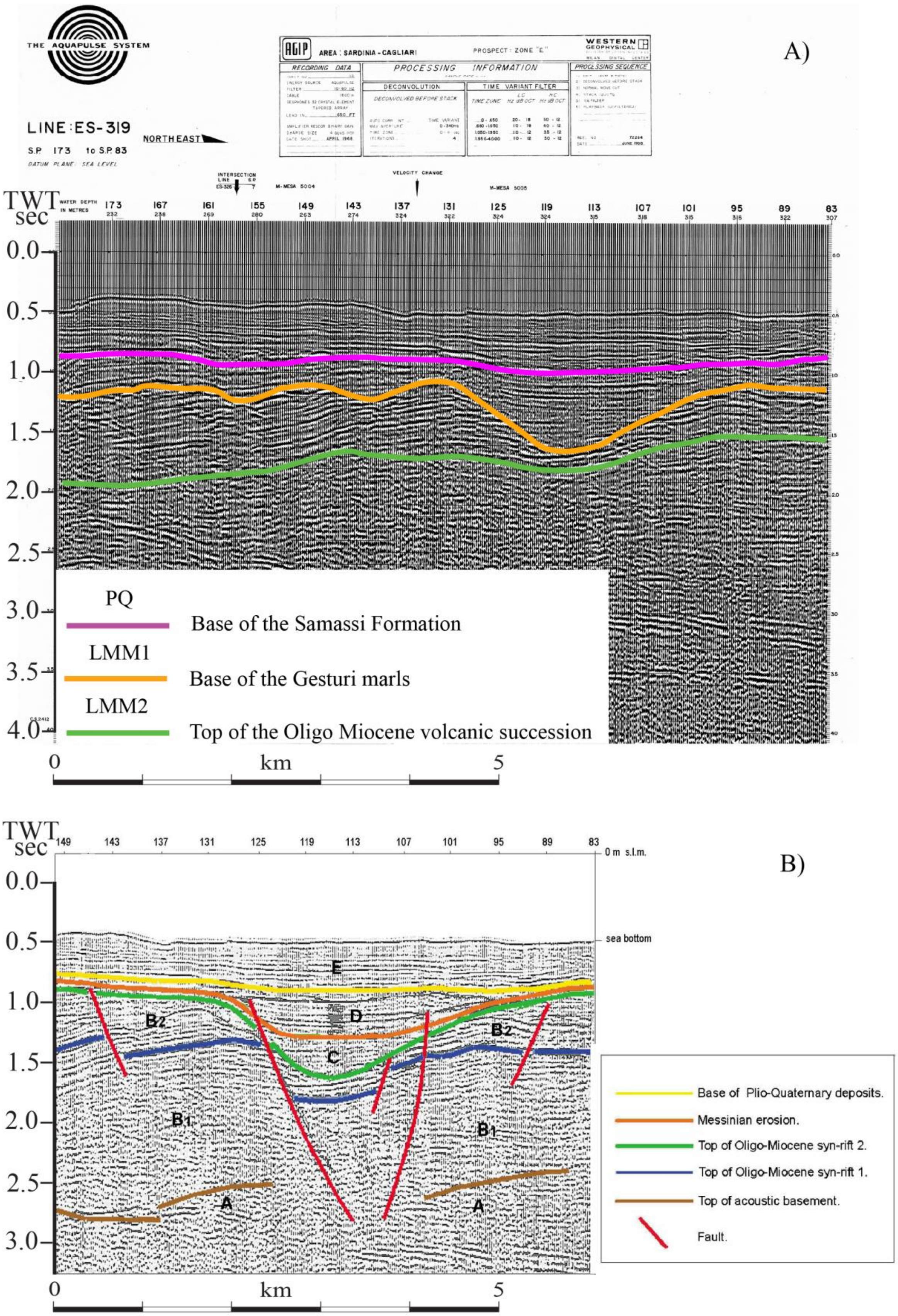


Fig.4.1- Line ES-319. A) interpretation according to this research; B) interpretation according to CASULA *et alii* (2001)

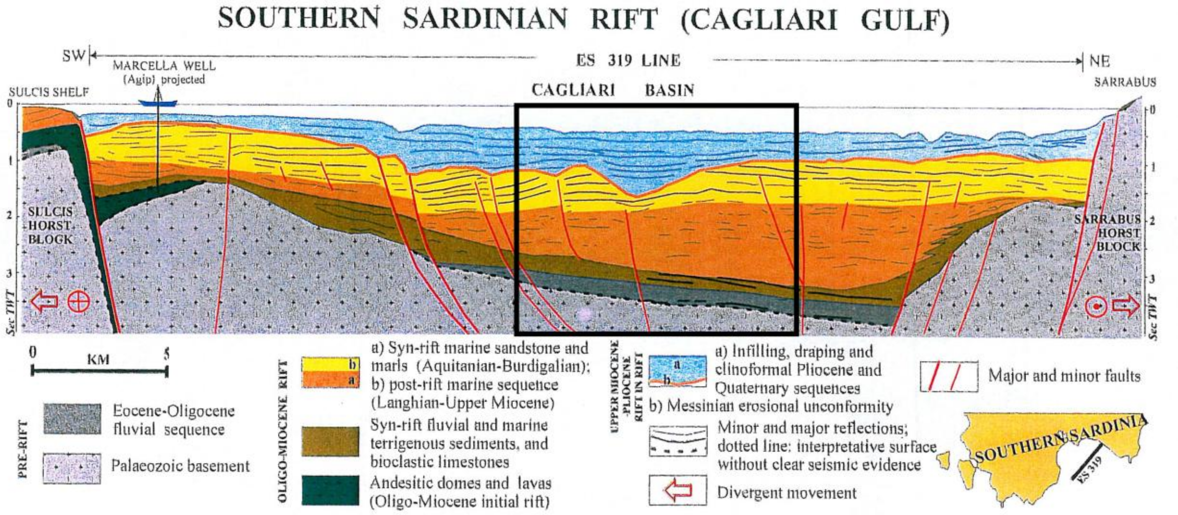


Fig.4.2- Line ES-319. Inerpretation according to FINETTI *et alii* (2005). In the black box is the part of the seismic lines shown in Fig.4.1 and Fig.4.2.

technique from one line to others. Thus, this angular unconformity, stronghly erosional, must be considerered related to the Miocene tectonic-sedimentary evolution.

How already illustrated in the previous chapter, the interpreted seismic lines confirm the occurrence of tectonic activity during Oligo-Miocene time. This is clearly shown where faults affecting the Oligo-Miocene succession are sealed by the Plio-Quaternary sediments or where the restoration of the faults affecting the Middle Pliocene erosional surface at the base of the Samassi formtion is not sufficient to restore also the deformation in the underlying Miocene succession (Line ES-328 in Fig.3.2.1, line 09 in Fig.3.2.2 and lines 01 and 04 in Fig.3.2.3).

Obviously, it is no possible to quantify the true displacement related to the Miocene tectonics because the throw and heave of the faults sealed by the Plio-Quaternary sediments are the minimum measurable. Where the restoration of the Middle-Pliocene erosional surface at the base of the Samassi formation is not sufficient to restore the deformation in the Miocene succession, the residual displacement is the minimum measurable because it is not possible to know how long the erosion affected the faulted Miocene succession before that the fault was reactivated in Pliocene time.

As noted in the introduction, according to CHERCHI & MONTADERT (1982; 1984) and CASULA *et alii* (2001), during Oligo-Miocene Sardinia was affected by the same extensional tectonics that affected a large area of south western Europe, showing the structures and deformations typical of the intracontinental extensional system such as the Suez Rift, the East African Rifts, the Rhine Graben, the North Sea, the Oslo Graben, controlled by major normal faults and tilted blocks.

By the interpretation of the seismic lines there are few evidences of growth faults or growth wedge-shaped geometries that should be the rule in the Miocene successions if the southern Sardinia was in a rift zone at that time. Thus, the model proposed by CARMIGNANI *et alii* (1994; 1995; 2001; 2004) and OGGIANO *et alii* (2009), according to which several Lower Miocene basins developed controlled by strike-slip tectonics in the arc zone related to the Apennine evolution, seems to be more appropriated. Particularly, the Campidano area was affected by transtensional tectonics with a dextral strike-slip fault in the western edge (Fig.1.4).

In the southern Campidano, the interpreted seismic lines show that the Miocene succession increasing in thickness toward the east (Line CA-304-92-V in Fig.3.2.2), allowing to suppose the occurrence of a faults in the eastern edge. This does not exclude that a strike slip fault could be active in the western edge too. Anyway, this data corroborates the occurrence of several Miocene basins. In fact, the eastern edge fault of the Campidano should have controlled the development of a basin N150 oriented to the west of Monastir while other basins developed eastward, as those of Gesturi and Isili (FUNEDDA *et alii*, 2012a; 2012b)

In the northern Campidano, instead, the Miocene succession seems to increase in thickness toward the center of the Oristano Gulf, as shown in the line 17 (Fig.3.2.5), that is N-S oriented. In the seismic line 2 (Fig.3.2.5), oriented W-E, the Miocene succession does not change its thickness approaching to the fault, but shows smaller thickness in the eastern part. The evidences from the lines 2 and 17 (Fig.3.2.5) can indicate that the Sinis fault, that controlled the deposition of the Plio-Quaternary succession (see following paragraph), reactivated a previous structure that bounded the western edge of a Miocene basin.

Unlike in Miocene, during Plio-Quaternary times, as illustrated in the chapter "Results", the master faults that controlled the deposition of the Samassi formation are located in the western edge in both the northern and southern Campidano. These two sectors are separated by the "Soglia di Sardara-Guspini" structural high, there the Oligo-Miocene volcanics crop out. According to CASULA *et alii* (2001) the "Soglia di Sardara-Guspini" is a transfer zone active and structured during Miocene and separated two opposing-polarity half-graben with the master faults in the western edge in the northern sector and in the eastern edge in the southern sector, as confirmed in this reasearch by the seismic interpretation. The fact that the "Soglia di Sardara-Guspini" was already structured before Pliocene is corroborate also by the reconstruction of the Middle Pliocene erosional surface at the base of the Samassi formation. In fact, towards the "Soglia di Sardara-Guspini" in both the northern and southern Campidano this surface lies above the Oligo-Miocene volcanics and thins up to missing where the Oligo-Miocene volcanics crop out, confirming that the basement above which the Samassi formation deposited was already structured.

Concerning the Upper Miocene, CASULA *et alii* (2001) in the southern Campidano identify a compressional phase during Messinian time that produced reverse faults and folds, not detected in this seismic interpretation. Obviously, this does not definitively exclude the occurrence of a compressional tectonics during Messinian, especially considering that the displacement affecting the Cagliari Limestones could be actually related to reverse faults. However, the folds ascribed to Messinian compressional tectonics by CASULA *et alii* (2001) are here interpreted as rollover anticlines related to the Plio-Quaternary extensional tectonis. In fact, the fault in the southeastern edge of the Campidano dips between 60° and 80° (Fig.3.2.3), because of its listricity, and this could be the cause of the rollover anticline that affected the Middle Pliocene erosional surface (Fig.3.3.1) and the underlying succession.

4.2- TECTONICS AND PALEOSTRESS DURING PLIO-PLEISTOCENE IN THE CAMPIDANO AREA

There are two time-markers useful to quantify the Plio-Pleistocene extension in southern Sardinia and they do not crop out continuously:

a) the Nuraghe Baboe Formation, Lower Miocene in age, that crops out in the Capo Frasca and Sinis peninsulas;

b) the Plio-Pleistocene basalt lava flows that crop out mainly in the central western side of the Island.

The discontinuty of these two time-markers both in outcrops and subsurface, does not allow to achieved reliable extension values of the Plio-Pleistocene tectonics.

The extension has been then calculated considering only the deformation affecting the Samassi formation that never crops out but has been mapped continuously in the seismic profiles in the subsurface of the Campidano area, where, furthermore, the faults affecting this formation can be detected (Fig.3.3.1 and Fig.3.3.2). The values of extension are achieved restoring in the cross-sections only the faults affecting the Middle Pliocene erosional surface at the base of the Samassi formation, to be sure that the measured deformation is completely related to Plio-Pleistocene tectonics. Unfortunately, the values of extensions are the minimum measurable because this surface are missing in the footwall of the edges faults, and the

Middle Pliocene erosional surface has been restored to the present day topography. However, in the northern Campidano, the basalts lava-flows that crop out in the Sinis peninsula sealed an erosional surface that is surely Plio-Pleistocene in age (considering the age of the basalts), and younger than that one sealed by the Samassi formation. In fact, in the hangingwall of the western edge fault two erosional surfaces can be detected: the oldest sealed by the Samassi formation and the youngest sealed by the basalts (Fig.4.3). This suggests that whereas the Samassi formation sealed the erosional surface (Fig.4.3b), stopping at that point the erosion, in the Sinis peninsulas erosion has continued up to the deposition of the basalt lava-flows (Fig.4.3c). Eastward, the Samassi formation thins up to missing close to the Monte Arci. Thus, the erosional surface at the base of the Samassi formation and the one sealed by the basalt lava-flows come to coincide (Fig.4.3c and Fig.4.3d). This suggests that the erosional surface sealed by the Samassi formation is diachronous, becoming younger eastward.

The western edge fault (Sinis fault) in the northern Campidano, where the two surfaces are discernible, is suitable to calculate the vertical slip rate.

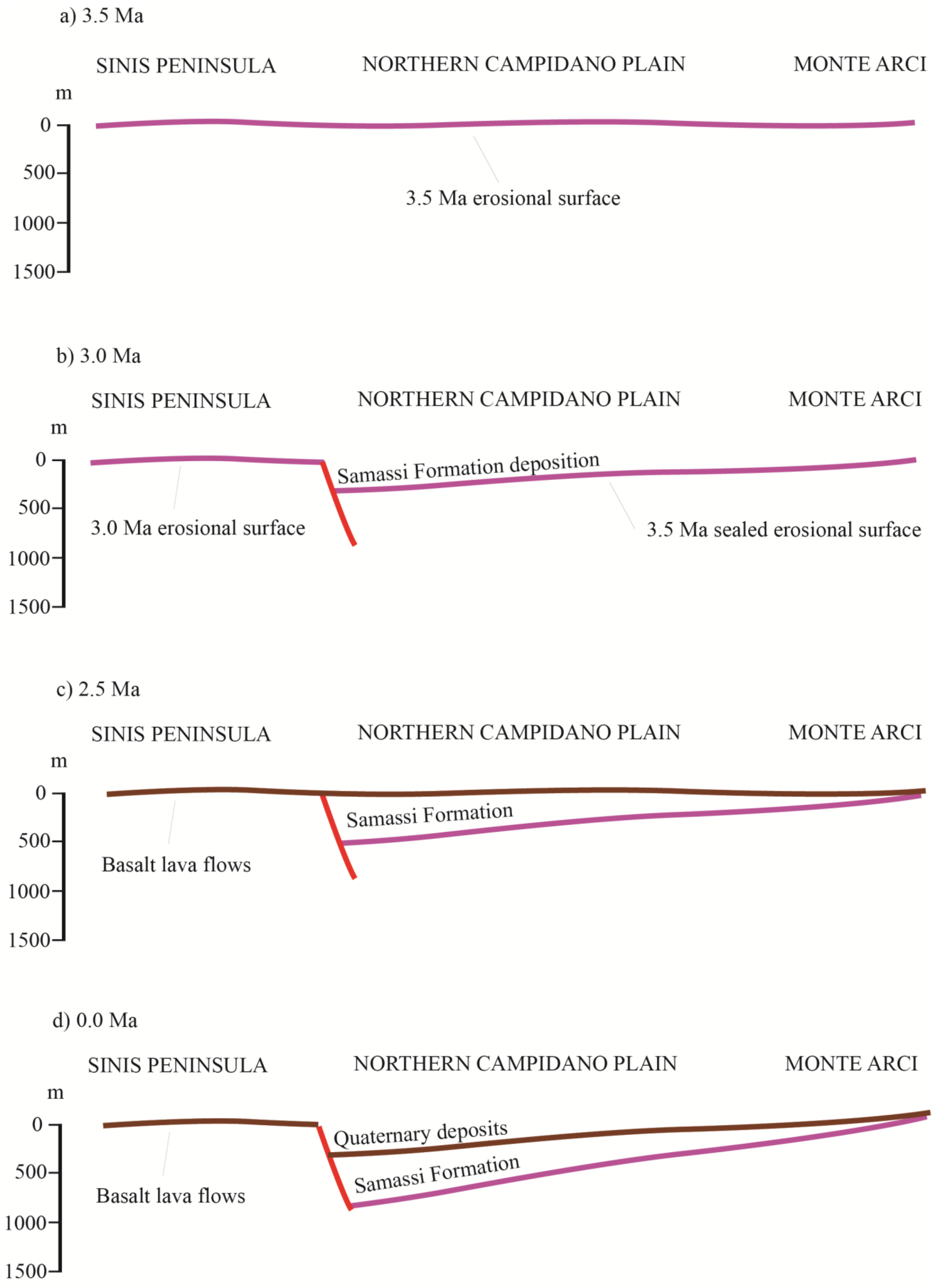


Fig.4.3- Schematic steps of the evolution of the erosional surfaces sealed by the Samassi Formation and the basalt lava flows. a) 3.5 Ma; b) 3.0 Ma; c) 2.5 Ma; d) Present day.

Therefore, using the Plio-Pleistocene time-markers that are the Middle-Pliocene erosional surface at the base of the Samassi formation and the Plio-Pleistocene basalts, vertical slip rate of 0.6 mm/yr has been calculated. The age ascribed to these markers are 3.5 Ma and 2.5 Ma respectively. Although the time-markers are not very accurated, the vertical slip rate of 0.6 mm/yr is in the order of magnitude typical of other half-grabens: 0.04 mm/yr to 0.3 mm/yr in the Maestrat grabens (eastern Spain) (SIMÓN *et alii*, 2013); 0.4 mm/yr to 6.7 mm/yr in the Gulf of Corinth (BELL *et alii*, 2008); 0.23 mm/yr in the Lower Rhine Graben and 0.32 mm/yr in the Swabian Jura zone (AHORNER, 1975); 0.1 mm/yr to 0.5 mm/yr in the Hatay graben (southern Turkey) (BOULTON & WHITTAKER, 2009); 0.5 mm/yr to 2.1 mm/yr in the Baikal rift (southeastern Russia) (SAN'KOV *et alii* 2000).

The vertical slip rate calculated has been used to constrain the age of the extensional deformation supposing that the deformation affecting the basalts had the same vertical slip rate. Thus the calculated extensional rates of 0.3 mm/yr in the northern Campidano and 0.4 mm/yr in the southern Campidano are constrained between 3.5 Ma and 1.77 Ma and 2.9 Ma and 1.5 Ma, respectively.

However, there are evidences of a deformation younger than the time limits used to calculate the extension rates. In fact, in the eastern edge of the southern Campidano, a fault seems to affect the Pleistocene deposits (PATTA, 2003) and the fault detected in the subsurface in the central part of the southern Campidano coincides in surface with the Flumini Mannu river. If the relationship between the present hydrography and the Samassi fault was confirmed, this fact suggests that the Samassi fault could be active up to recent times. Furthermore, other evidences of more recent tectonics occur also in southwestern (BUTTAU *et alii*, 2011) and eastern Sardinia (CAROBENE, 1972; COLTORTI *et alii*, 2006; FERRANTI *et alii*, 2006).

Thus, while the vertical slip rate calculated for the deposition of the Samassi formation is quite realistic, considering that is temporally constrained and does not show differences compared to others measured in similar tectonic settings, the assumption that the deformation affecting the Plio-Pleistocene basalts continued with the same rates can not be completely reliable.

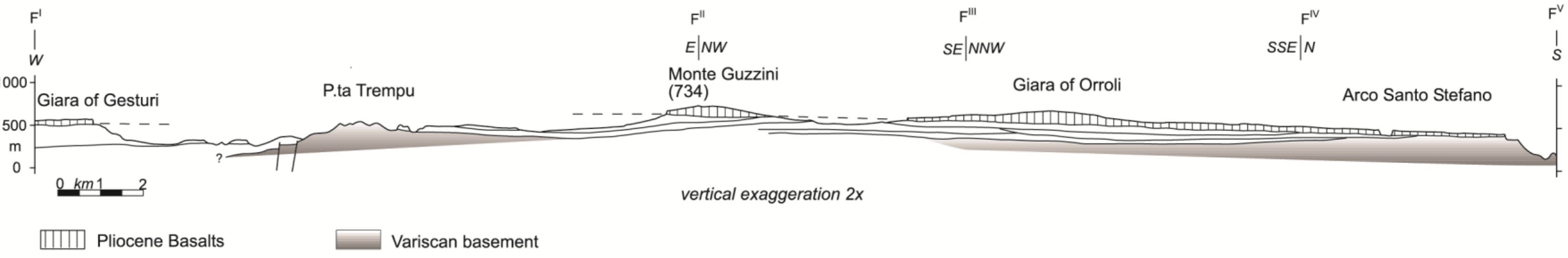
If it is considered that the tectonics affecting the basalts lasted up to now, then, considering the age of 2.5 Ma of the basalts detected in the subsurface at 440 m, a vertical slip rate of approximately 0.18 mm/yr can be calculated. Also this value can be reliable if compared with the examples cited above. Furthermore, it corroborates the value of surface uplift that can be estimated for the erosional surface sealed by the basalts of the "giare" to the east of

Campidano (Fig.4.4). In fact, if a marine origin is hypotesized for this surface (COLTORTI *et alii*, 2006), then, considering that now it occurs up to 550 m above the sea level and the age of 3.0 Ma of the basalts that seal it, an uplift rate of 0.18 mm/yr can be calculated. However, considering the erosional surface sealed by the basalts in the Sinis peninsula approximately at 50 m above the sea level, that can be correlated directly with those detected in the subsurface in the northern Campidano (Fig.3.2.5), ascribing to it an age of 2.5 Ma, an uplift rate of 0.02 mm/yr is calculated. The differences in surface uplift rates and vertical slip rates suggest that tectonic activity may have had changes in rates of deformation during the several time intervals marked by the different ages of the erosional surfaces: 3.5 Ma that sealed by the Samassi formation, 3.0 Ma that sealed by the basalts in the central Sardinia, 2.5 Ma that sealed by the basalts in the northern Campidano.

Furthermore, the difference in elevation between the higher basalts that crop out in the central Sardinia (approximately 700 m in the Orroli basalt plateau) and those detected in the subsurface (-440 m in the northern Campidano, Fig.3.2.5), although they sealed marine erosional surface (COLTORTI *et alii*, 2006) that are not perfectly of the same age, is related to tectonic activity that is at least Pleistocene in age. Therefore, during the whole Plio-Quaternary tectonics, considering the Middle Pliocene erosional surface at the base of the Samassi formation detected at -1,100 m in the northern Campidano, vertical displacements on the order of 1,800 m can be inferred. This data does not take in account the diagenetic and tectonic compaction occurred on these sediments during tectonic evolution, thus is rational to image higher vertical displacement.

The calculated paleostress field indicates that the tectonic activity in the Campidano area during Pliocene times was characterized by extension oriented roughly E-W in the northern and NW-SE in the southern Campidano.

The paleostress field has been calculated restoring the 3D surface of the Middle Pliocene erosional surface (chapter 3.5). Depending on the absence of kinematic indicators acquirable in the field, the method of rigid block restoration in map view has been used. This does not allow to know the slip directions in the western and eastern edges faults of the southern Campidano. In fact, without the reference level in the footwall, the method become inapplicable because the footwall cut-off line can not be mapped. If the shape of the footwall cut-off map is hypothesized, this can cause mistakes during the restoration in the movement of the blocks closing a gap with a shape that is not true and therefore extrapolate incorrect movement vectors.



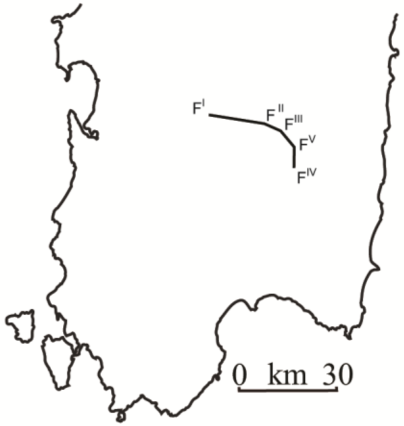


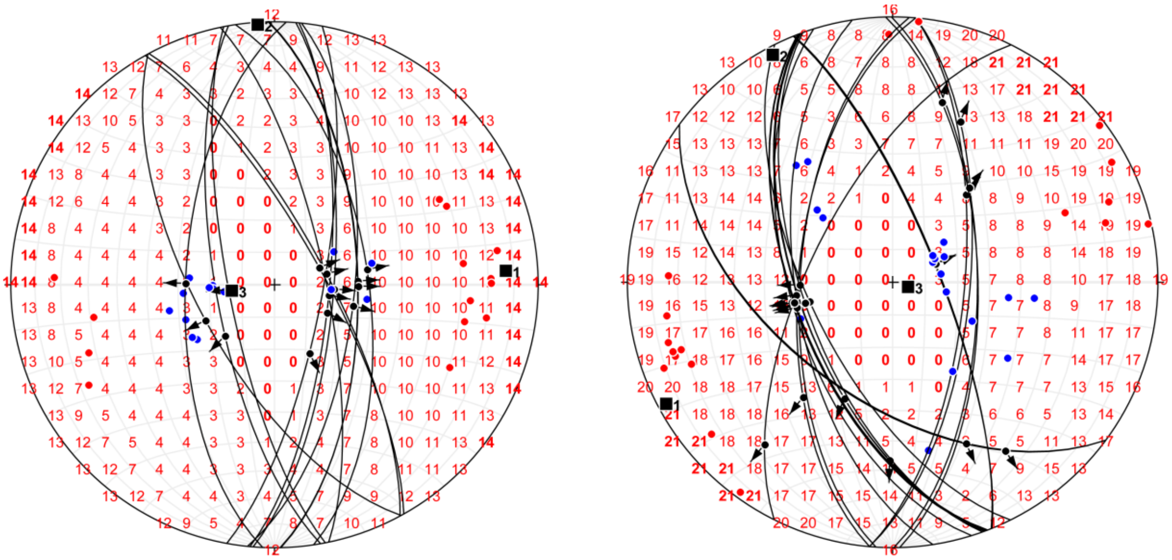
Fig.4.4- Geological cross-section showing the erosional surface sealed by the Pliocene basalt lava-flows (modified from FUNEDDA *et alii*, 2012).

Differences occurs in the type of faults characterizing the northern and southern Campidano. In fact, the faults detected in the north are mainly dip-slip, whereas in the south several faults are oblique-slip with sinistral component. This can be due to the reactivation of previous structures.

Also the differences in the orientation of the extension between the northern and southern Campidano can be related to the reactivation of previous faults that locally can modified the stress field.

It is important to consider that the northern and southern Campidano are separated by the structural high of Guspini-Sardara and that the stress field could be originally different. Furthermore, if the younger age of the surface restored in the southern Campidano is compared with the same in the northern Campidano, the different time in which the paleostress field has been measured can be the reason of the discrepancy between northern and southern Campidano.

In addition to this, imprecisions in the measure of the paleostress axes can arise from the method of inversion used. By the right dihedra method (ANGELIER & MECHLER, 1977), the fault slip data are transformed into a focal mechanism, thus, for each fault, an auxiliary plane perpendicular to the movement vector has to be reconstruct. Once that all the fault slip data are plotted, the residual P (compressional) and T (extensional) domains can be large and the stress axes σ_1 and σ_3 have no reason to occupy a central orientation in these domains, and can lie near their edges as well. This margin of error explains why the results, although reliable, are incomplete. In Fig.4.5, the same stereoplots illustrated in the chapter "Results" are shows as plot of number to demonstrate the variability in the orientation that the calculated stress axes could have.



a) Northern Campidano

b) Southern Campidano

Fig.4.5- Plots of number showing the common P and T domains. In both the plots 0 represent the common P domain. In the northern Campidano (a) the common T domain is represented by 14 and in the southern Campidano (b) by 21. Blue points are the P-axes and red points are the T-axes. The fault-slip data and the principal stress axes are also shown.

4.3- GEODYNAMIC SETTING

The Plio-Pleistocene tectonics affecting Sardinia is obviously related to the geodynamic evolution of the western Mediterranean, where, starting from the upper Miocene, the most important geodynamic event is the opening of the southern Tyrrhenian basin.

The southern Tyrrhenian basin are separated from the northern sector of the Tyrrhenian basin by an important magnetic and tectonic feature that coincides roughly with the 41° parallel (Fig.4.6). The main structures that characterize the southern Tyrrhenian basin are (Fig.4.6), eastward: the eastern Sardinian margin, the Sardinian basin, the Cornaglia terrace, that is a transitional crust zone between the continental crust that occurs in the Sardinian Basin and the oceanic crust that occurs in the Vavilov Basin (Fig.1.18). In fact, the Vavilov basin are related to a very short-lived drifting stage that produced the emplacement of few square kilometres of oceanic crust during Pliocene (SARTORI *et alii*, 2004). In the southeastern sector, where extension migrated after Pliocene (KASTENS *et alii*, 1998; SARTORI, 1990), emplacement of oceanic crust occurred in the Marsili Basin (Fig.1.18).

In particular, the evolution of the southern Sardinia seems to be strictly related to the evolution of the sector of the Tyrrhenian basin located roughly to the south of the 40° parallel, that coincides with an inherited Mesozoic discontinuity reactivated as a transfer zone during the Neogene (Orosey Canyon Line) (Fig.4.6). This can be infer from both the ages and the similarities of the stuctures in the eastern Sardinian margin and Campidano area.

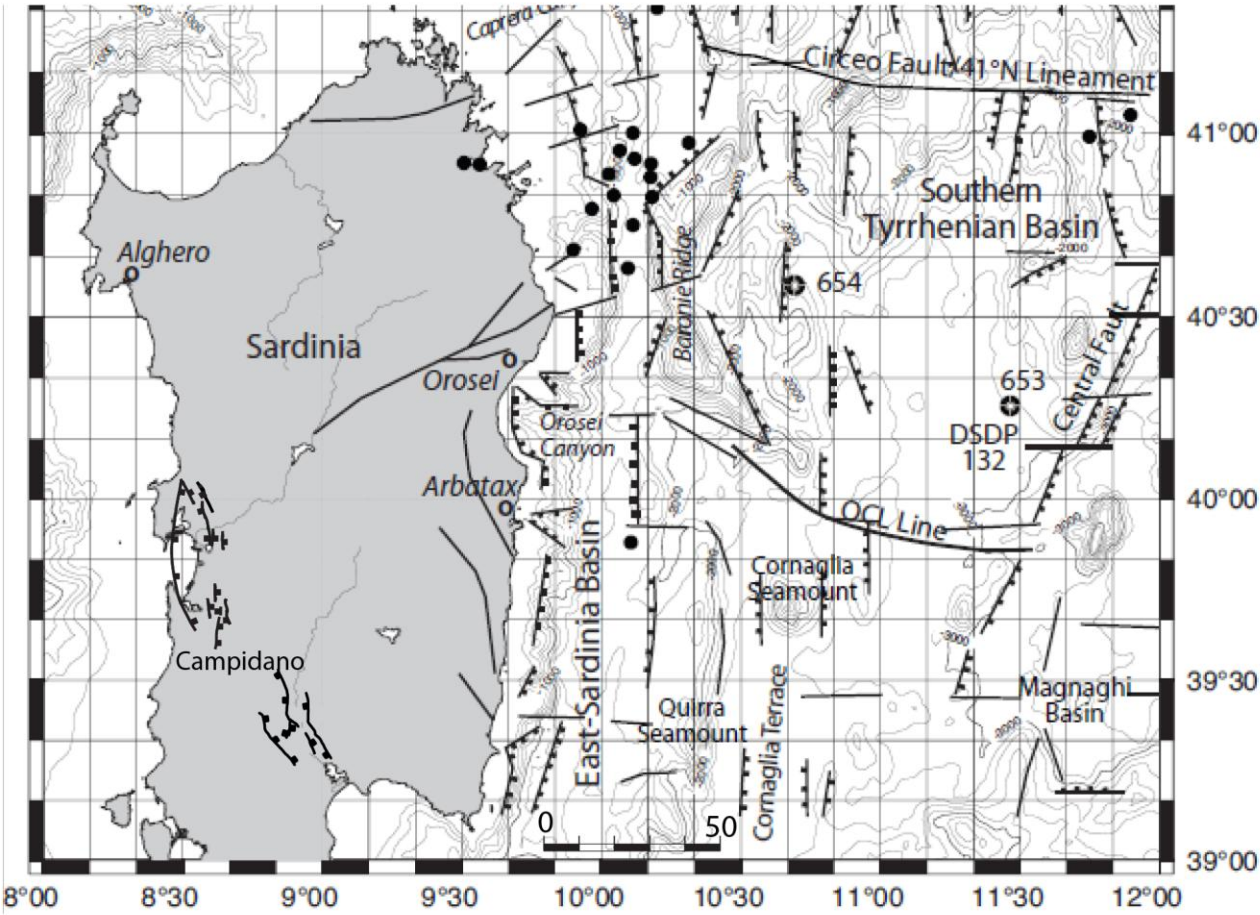


Fig.4.6- Tectonic structures of the southwestern Tyrrhenian basin (Gaullier *et alii*, in press) and Campidano graben (this research).

The Sardinian Basin (Fig.4.7) is a half-graben about 20 km wide and 100 km long, but, on the contrary of the Campidano, the Plio-Pleistocene master fault is in the eastern edge and dips to the west. The stratigraphic succession recognised is the same that those in the Campidano. In particular, concerning the Plio-Quaternary succession, SELLI & FABBRI (1971) detected two unconformities: the first, named X, is at the base of the succession that is Recent to part of Pliocene in age; the second, named Y, is at the base of the succession that is Pliocene to latest Messinian (?) in age. These unconformity are perfectly comparable whit the erosional surfaces detected at the base of the Samassi and Nuraghe Baboe formations, respectively.

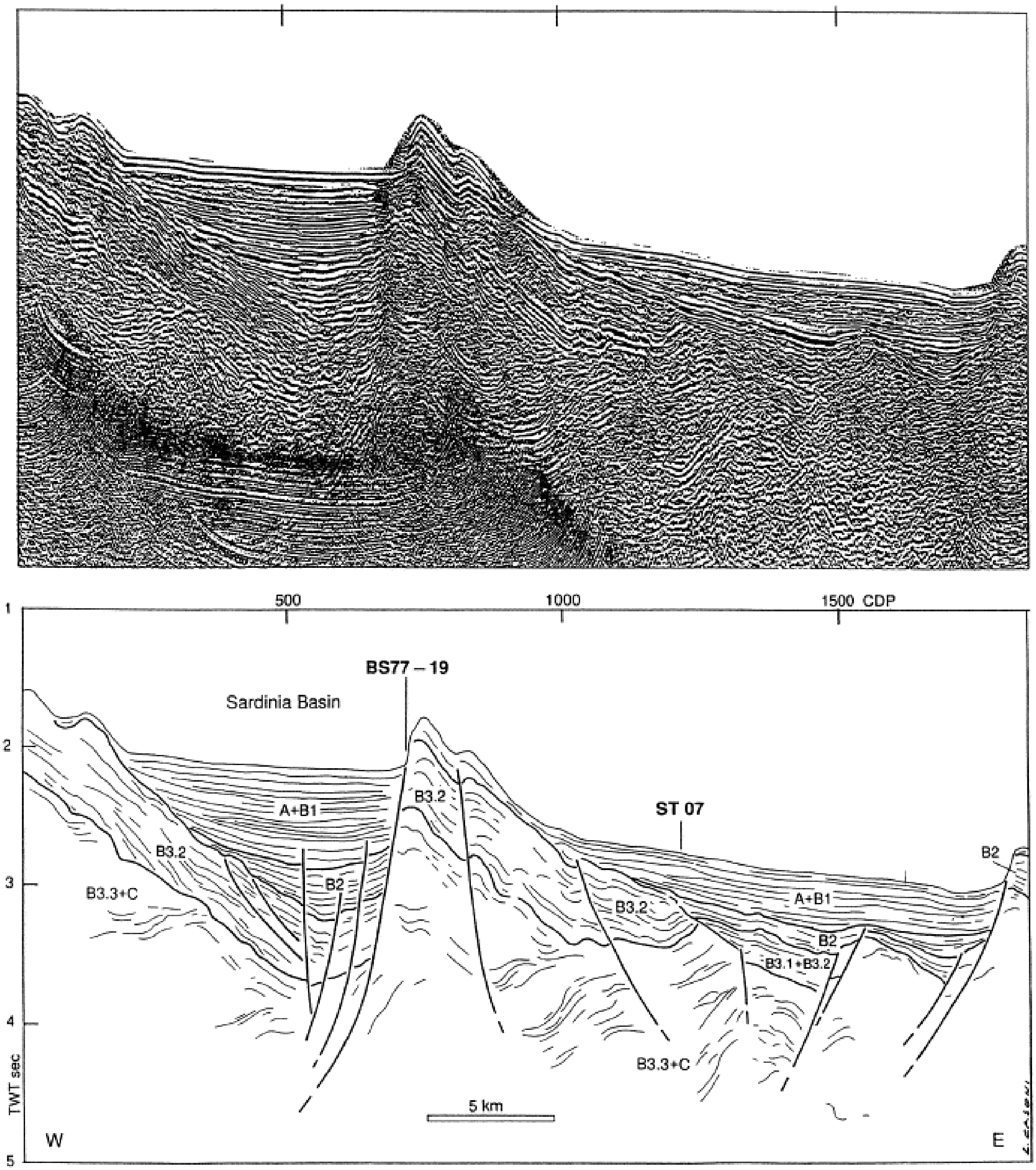


Fig.4.7- MCS Line ST08, through the Sardinian Basin (SARTORI *et alii*, 2001). A: Upper Pliocene to Recent; B1: Upper Messinian to Pliocene; B2: Messinian; B3.1: Upper Tortonian to Lower Messinian; B3.2: Tortonian; B3.3: Upper Oligocene to Middle Miocene; C: Acoustic Basement.

Also the throw of the faults that affected these unconformities, roughly 1000 m (FABBRI & NANNI, 1980) is comparable with those detected in this study in the Campidano.

Differences occur in the times of structuring: the Sardinian Basin seems to have begun its structuring in the Upper Tortonian, as shown by the syn-tectonic deposits that are Messinian in age (B2 seismic-unit in Fig.4.7, SARTORI *et alii*, 2001). In the Campidano, instead, no evidences of Upper Miocene syn-tectonic deposit occur. The Upper Miocene succession in the sourrounding areas of the Campidano plain crops out only in the Cagliari hills and Sinis and Capo Frasca penisulas, and, in the subsurface is not continuous and does not show depositional geometries that can be related to tectonic activity. Furthermore, the same characteristics are shown by the Lower Pliocene succession, thus, it can be infer that the structuring in the Campidano started when the erosional surface at the base of the Samassi formation and above the Lower Pliocene succession began to be "fossilized" that is Middle Pliocene (Fig.4.3).

The beginning of the tectonics in the Campidano area is roughly simultaneous with the opening of the Vavilov Basin, that is located to the east of the Cornaglia Terrace that separates it from the Sardinian Basin.

Therefore, it seems that the extensional tectonics started in the Upper Miocene in the Sardinian Basin and Cornaglia Terrace and migrated westward in Sardinia and eastward in the Vavilov Basin. This is corroborated also by the ages of the volcanics. In fact, the sediments dredged up at the top of the volcanic Quirra Seamount are Lower Pliocene in age and the radiometric age of the basalts of Capo Ferrato are Messinian in age (6.6-6.4 Ma). During the opening of the Vavilov Basin, started at 4.3 Ma, volcanic attivity (4.4 Ma) started in Sardinia on the western edge of the Campidano (close to the Guspini village) and in the Middle Pliocene the bulk of volcanism occurred in the Island.

According to these data, the extensional tectonics affecting the southern Sardinia in the Pliocene can be directly related to the geodynamic evolution of the southern Tyrrhenian Basin. Furthermore, the direction of extension (Fig.4.8) changed from E-W in the Late Tortonian-Zanclean to SW-NE in the Zanclean-Piacenzian (CARMINATI *et alii*, 1998), and corroborate the extension directions achieved by the paleostress fields in the northern Campidano (E-W) and southern Campidano (SW-NE). In fact, if the younger age of the erosional surface at the base of the Samassi formation in the southern Campidano would confirmed compared to that in the northern Campidano, then the change in the extension direction in the Island can be due to the general change in the extension direction during the evolution in the Tyrrhenian Basin.

Concerning to the Pleistocene evolution, it seems that the same age tectonics recognized in Sardinia could not be related directly to the evolution in the Tyrrhenian Basin. In fact, the evolution in the Tyrrhenian Basin continued in the Pleistocene with the opening of the Marsili

Basin (2 Ma) and with extension direction roughly towards SE, and the formation of oceanic crust, separated from the Vavilov Basin by a zone of continental crust (Fig.1.15). Thus, the recent uplift affecting the southern Sardinia described in the previuos paragraph, is most likely related to the litospheric structure inherited from the pre-Pliocene geodynamic evolution of the western Mediterranean.

In extensional context, two different mechanisms can cause uplift (STUWE, 2007): the first is when a heterogeneous extension occur and the mantle lithosphere is stretched more than the crust (Fig.4.9a); the second is when a homogeneous extension affects the entire lithosphere where the mantle lithosphere constitutes a large proportion of the lithosphere by thickness (Fig.4.9b).

Actually, in Sardinia the lithosphere is roughly 70 km thick, constitued by 30 km of crust and 40 km of mantle lithosphere. The disequilibrium is caused by the thin mantle lithosphere and, having the crust a normal thickness, the second mechanism cited above can not be responsible of the uplift. In fact, a homogeneus extension can not thin up to 40 km the mantle lithosphere (that to cause uplift had to be a large proportion of the lithosphere) and maintain a crust of 30 km. Furthermore, the data achieved during this research show low percentage of extension.

If instead the extension has been heterogeneous, stretching more the mantle lithosphere than the crust, then the low percentage of extension measured in the crust and the thinned mantle lithosphere could explain the uplift.

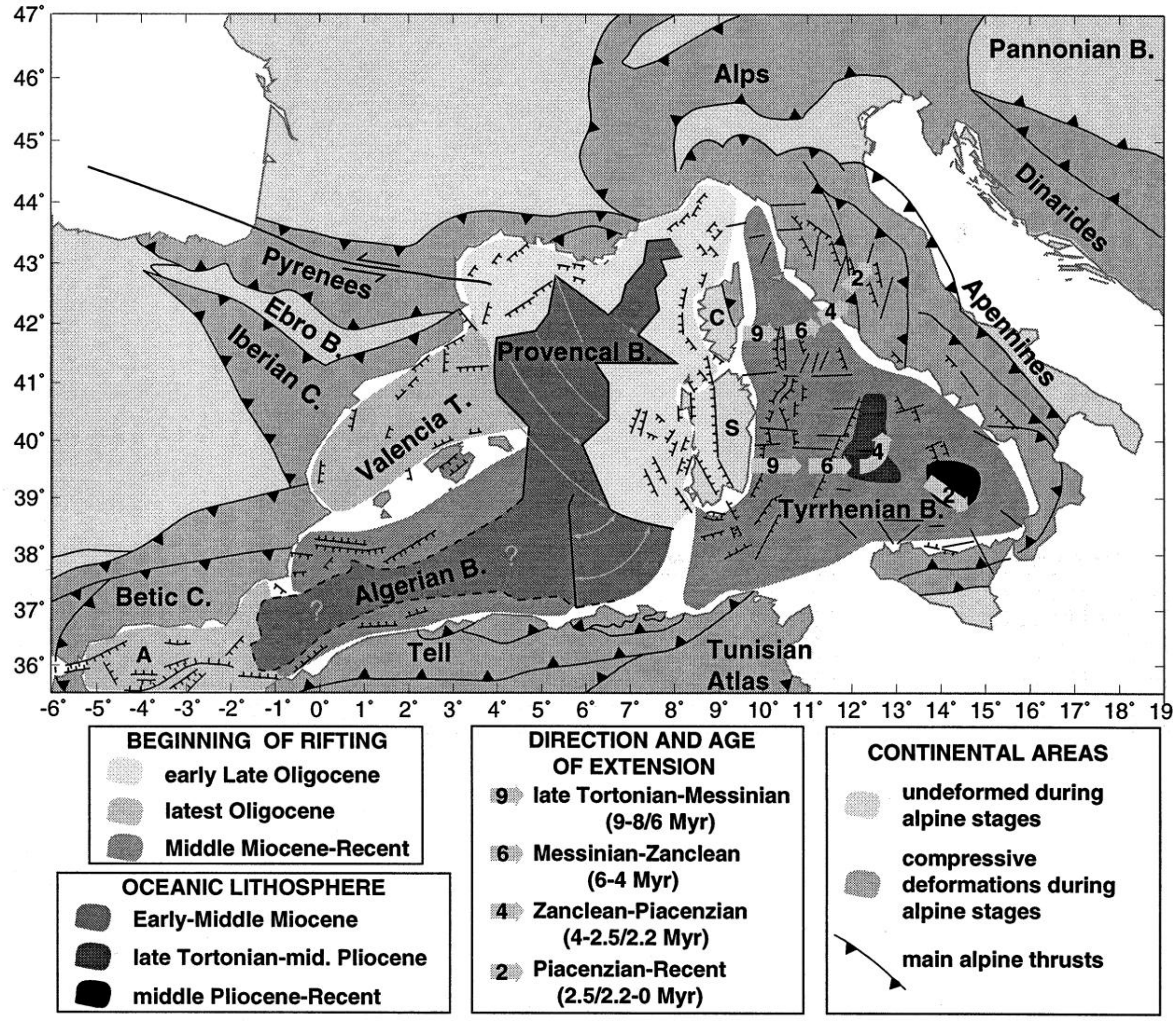


Fig.4.8- Tectonic sketch of the western Mediterranean area (CARMINATI *et alii*, 1998). The directions and ages of extension in the northern and southern Tyrrhenian Basin are also shown. A: Alboran Basin; C: Corsica; S: Sardinia.

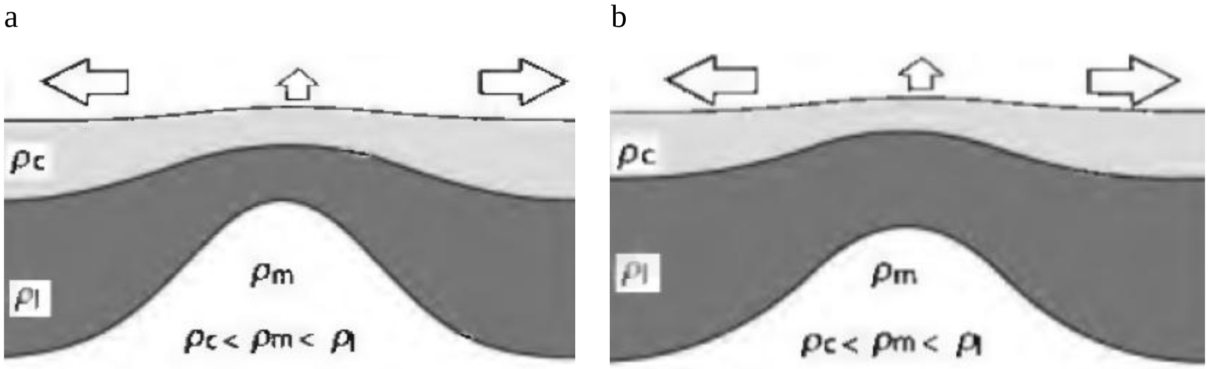


Fig.4.9- Mechanism of extension causing uplift (STUWE, 2007). In a extension causes surface uplift because the mantle lithosphere is stretched more than the crust. In b extension causes surface uplift because the mantle lithosphere constitutes a large proportion of the lithosphere by thickness.

Clearly, not only extensional tectonics can cause the thinning of the lithosphere. The thinning of the mantle lithosphere can be connected also with the process of intensive convective heating (thermal thinning).

The uplift of an area characterizes its geomorphic signatures, thus some hypothesis can be made considering the present day topography of the southern Sardinia. In the Sulcis-Iglesiente block (to the west of the Campidano plain) the topographic morphology are more irregular than in the Sarrabus-Gerrei-Sarcidano block (to the east of the Campidano plain) where several flat surfaces occur at high altitude (Fig.4.10 and Fig.4.11), approximately up to 700 m for the Plio-Pleistocene basalt lava-flows and up to 1000 m for the Mesozoic covers. Furthermore, to the west of the Campidano plain no Miocene sedimentary successions occur whereas to the east the Miocene marine succession is peneplaned and onlaps on the Palaeozoic basement. These evidences suggest that the Sulcis-Iglesiente block was uplifted before the Sarrabus-Gerrei-Sarcidano block, causing the non-deposition of the Miocene marine succession and the present day irregular topography without preserved flat surfaces at high topography to the west of the Campidano plain.

These observations are in agreement with the model to explain the generalized uplift affecting the Sardinia-Corsica block proposed by DOGLIONI *et alii* (2004) that related it to the opening of the Provençal basin to the west. The mantle upraised along the rift zones, determine partial melting and a residual depleted mantle with lower density of 20-60 kg/m^3 than the normal mantle. This residual part of the mantle, less dense, when displaced to the east should generate a mass deficit with respect to the western limb of the ridge where this low density mantle did not propagate. Moving eastward, the depleted mantle should be uplifted the Sulcis-Iglesiente block before the Sarrabus-Gerrei-Sarcidano block, in accord with the geomorphic evidences.

A lower density of 20-60 kg/m^3 of the mantle litosphere involves that the density of the mantle lithosphere that moves eastward below the Sardinia is 3.28-3.24 gr/cm^3 if a mean density of 3.3 gr/cm^3 of a normal mantle lithosphere is considered. In percentage, then, the density decreases of 0.6-1.8%. A normal 120 km thick lithosphere, including a 30 km thick crust, undergoes an uplift of 1,200 m if it is affected by a lowering of the density of 1% (BOILLOT *et alii*, 2008). Therefore, assuming a normal lithosphere below the Sardinia before the uplift and that the lowering of the density affected only the mantle lithosphere (90 km) because the present day thickness of the crust is 30 km suggesting that no changes in volume due to the lowering of density occur, an uplift of 540 m or 1,620 m can be inferred for a decreasing of density of 0.6% or 1.8% respectively. Instead, if the present day thickness of the mantle lithosphere is considered (40 km), then an uplift of 240 m or 720 m can be inferred.

The values of uplift achieved considering the lowering of the mantle density proposed by DOGLIONI *et alii* (2004) are in the order of magnitude of those that can be inferred by the present day geology and topography and allow to consider this model appropriate to explain the recent uplift affecting Sardinia.

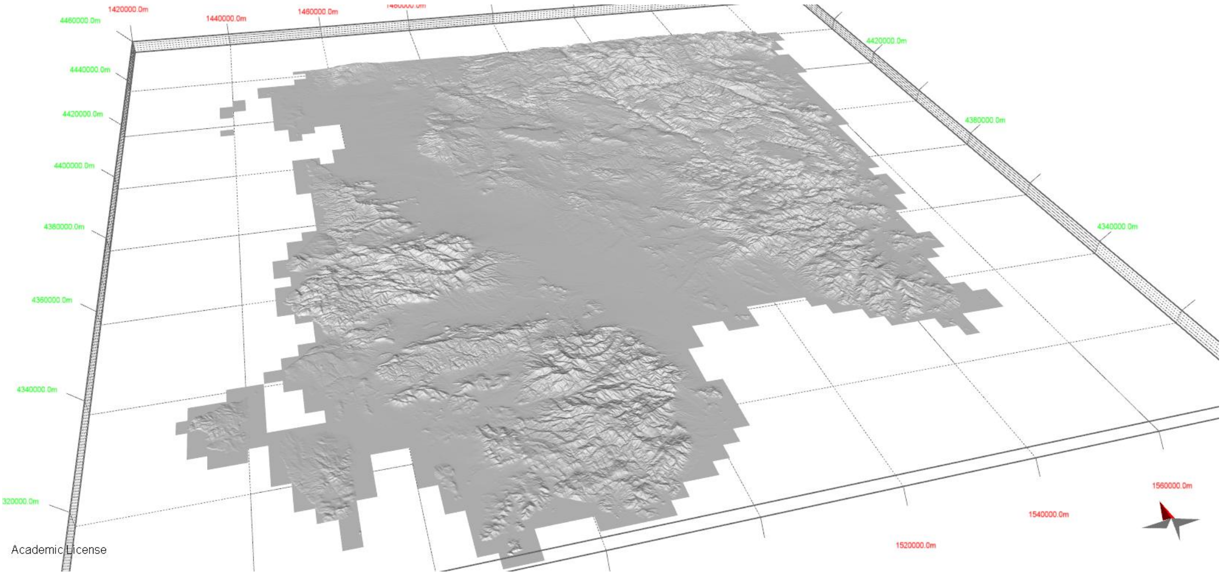


Fig.4.10- DEM of the southern Sardinia. The Sulcis-Iglesiente block (to the west of the Campidano plain) shows more irregular topography than the Sarrabus-Gerrei-Sarcidano block (to the east of the Campidano plain), where several flat surfaces occur at high altitude.

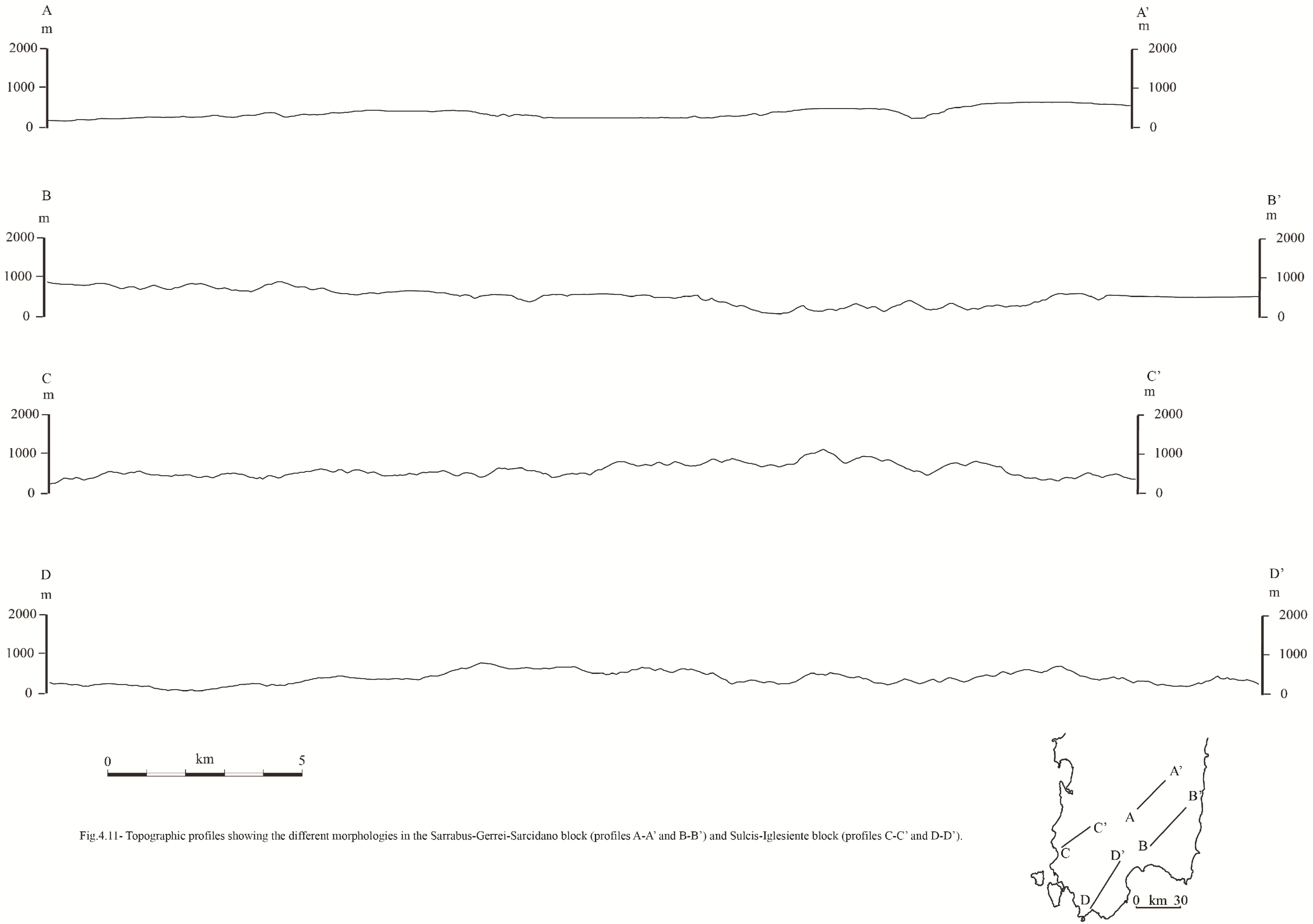


Fig.4.11- Topographic profiles showing the different morphologies in the Sarrabus-Gerrei-Sarcidano block (profiles A-A’ and B-B’) and Sulcis-Iglesiente block (profiles C-C’ and D-D’).

5 CONCLUSIONS

During this research, the seismic lines acquired in the Campidano plain and off-shore of Cagliari Gulf up to the 90th years of the last century, calibrated with the available four deep wells drilled for hydrocarbon research purposes, have been interpreted aimed at the understanding of the recent structural setting of the so-called Campidano graben, that is the most important structure related to the Plio-Quaternary evolution of the Island.

The main results achieved are:
- the 3D model of the Middle Pliocene erosional surface at the base of the Samassi formation detected in the subsurface of the Campidano plain;
- the extension values and the deformation rates affecting the Campidano area during Plio-Quaternary times;
- the reconstruction of the paleostress field active during Pliocene time in the Campidano graben;
- a comparison between the structural setting of the Campidano and the structural setting of the southeastern Sardinian margin;
- the integration of the data achieved during this research with the data available from literature on the geodynamic evolution of the western Mediterranean, in particular about the opening of the Tyrrhenian Basin.

The 3D model of the Middle Pliocene erosional surface has been built using the two-way time structural maps of this surface carried out in both the northern and southern Campidano. This surface shows a gently rolling landscape, typical of the erosion and planation surface developed in continental environments, both in the subsurface of the southern and northern Campidano plain. In the Campidano of Oristano, the maximum depth of the bottom of the Samassi formation is approximately -1100 m, while in the southern it is roughly -900 m (mean velocity assigned 2 km/s).

The two-way time structural maps show that both the northern and the southern Campidano graben are bounded in the western edges by master faults dipping to the east, but differences arise in the trends of the faults: mostly N-S in the northern Campidano and NW-SE in the southern Campidano.

N-S normal faults affected the whole Samassi formation and the within-plate basalts that post-date it, so we may admit that an important extension occurred after its deposition, in Pleistocene time.

The structures from seismic interpretation, that characterized the Plio-Quaternary evolution of the so-called Campidano graben have been validated during the drafting of the two-way time maps and with the structural and stratigraphic data available on surface. This allowed to construct a validated 3D model from which achieved the most possible reliable values of extension and paleostress.

To quantify the Plio-Quaternary deformation in southern Sardinia the 3D model of the Middle-Pliocene erosional surface (roughly 3.5 Ma in age) has been considered. In the southern Campidano, extension values that range from 205 m to 596 m and the percentage of extension from 1.65% to 5.72% are calculated. In the northern Campidano extension values range from 171 m to 465 m and percentage of extension from 0.84% to 2.50%.

Although the Plio-Pleistocene time-markers (3.5 Ma the erosional surface at the base of the Samassi formation and 2.5 Ma the surface sealed by the basalt lava flows in northern Campidano and a reflector calibrated with the Campidano1 well in the southern Campidano) are not very well constrained, they allow to estimate the vertical slip rate (0,6 mm/yr) and the extension rate (0,3 mm/yr in the northern Campidano and 0,4 mm/yr in the southern Campidano).

Considering the erosional surface sealed by the basalt-lava flows of the "giare" to the east of Campidano that occurs up to 550 m above the sea level and the age of 3.0 Ma of the basalts that seal it, an uplift rate of 0.18 mm/yr can be calculated if a marine origin for this surface is confirmed. Furthermore, the difference in elevation between the higher basalts that crop out in the central Sardinia (approximately 700 m in the Orroli basalt plateau) and those detected in the subsurface (-440 m in the northern Campidano) is related to tectonic activity that is at least Pleistocene in age. Therefore, during the whole Plio-Quaternary tectonics, considering the Middle Pliocene erosional surface at the base of the Samassi formation detected at -1100 m in the northern Campidano, vertical displacements on the order of 1,800 m can be inferred.

The paleostress field active during Pliocene time in the Campidano area has been reconstructed using the movement vector on the fault plane achieved from the restoration of the Middle Pliocene erosional surface in both the northern and southern Campidano using different methods.

In the northern Campidano, an extension oriented roughly E-W, with the principal stress axes: σ_1=263/77 σ_2=356/1 σ_3=86/13, has be inferred. In the southern Campidano, an extension oriented roughly ENE-WSW, with the principal stress axes: σ_1=105/85 σ_2=332/3 σ_3=242/3.

The evolution during Pliocene in the southern Sardinia seems to be strictly related with the evolution of the sector of the southern Tyrrhenian basin located roughly south of the 40° parallel. This can be infer from the similarities in ages and stuctures in the eastern Sardinian margin and Campidano area. It seems that the extensional tectonics started in the Upper Miocene in the Sardinian Basin and Cornaglia Terrace and migrated westward in Sardinia and eastward in the Vavilov Basin. Therefore, the extensional tectonics affecting the southern Sardinia in the Pliocene can be directly related to the geodynamic evolution of the southern Tyrrhenian Basin.

Concerning the Pliocene tectonics affecting Sardinia, it seems to be directly related to the beginning of the extension in the Tyrrhenian Basin, due to the eastward roll back of the subducting Adriatic plate.

It seems that the Pleistocene tectonics recognized in Sardinia can not be related directly with the evolution of the Tyrrhenian Basin, although the extensional tectonics continued with the opening of the Marsili Basin. Thus, the recent uplift affecting the southern Sardinia is most likely related to the lithospheric structure inherited from the pre-Pliocene geodynamic evolution of the western Mediterranean, during which the lowering of the density in the mantle lithosphere could be caused an uplift up to 1620 m, considering a normal thick mantle lithosphere, or up to 720 m, considering the present day thinned mantle lithosphere, or by the thinning of the mantle lithosphere connected with process of intensive convective heating (thermal thinning).

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