DAY 2: Alta Val d’Agri

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The high Agri River valley (Alta Val d’Agri; Fig. 2.1) is a WNW-ESE oriented intramontane basin located in the axial zone of the southern Apennines. Here, a Quaternary fault system dissects the pre-existing fold and thrust belt. The latter is characterised by the tectonic superposition of allochthonous units, completely detached from their original substratum, onto the foreland succession of the Apulian Platform (e.g. Mostardini & Merlini, 1986; Cello et al., 1990; Carbone et al., 1991; Casero et al., 1991; Cinque et al., 1993). The latter consists almost entirely of Mesozoic and Tertiary shallow marine carbonates, stratigraphically overlain by Pliocene foredeep shales of variable thickness. Available subsurface data in the study area indicate that the overall thickness of the Apulian Platform is between 6-7 km, thickening gradually to 8-9 km in the foreland (Shiner et al., in press). The deep stratigraphy of the Apulian platform is known from deep hydrocarbon wells located on the Apulian foreland, where the basal part of the section is made up of the Upper Triassic interbedded anhydrites and dolomites comprising the Burano Formation. Beneath the Burano Formation, several deep wells (Puglia-1, Gargano-1; Bosellini et al., 1993) have also encountered a Permian to Lower Triassic mixed carbonate-clastic section of unknown thickness and of shallow marine-continental affinity.

The hinterland section of the Apulian platform, which is almost entirely buried beneath the allochthon and the foredeep deposits of the Bradanic trough, was involved in the final phases of compression within the southern Apennines (e.g. Mostardini & Merlini, 1986; Cello et al., 1990). As a result, the reverse-fault related, open, long wavelength-high amplitude fold structures that form the hydrocarbon traps in the area of Day 2 of the field trip were generated (e.g. Menardi Noguera & Rea, 2000; Shiner et al., in press).

At surface, the structure of the thrust belt is dominated by the superposition of tectonic units made of Mesozoic-Palaeogene shallow marine and slope carbonates on top of the Lagonegro basin units (Scandone, 1972). The latter are involved in mainly NW-SE to N-S trending folds and thrusts (e.g. Scandone, 1972; Carbone et al., 1991; Mazzoli et al., 2001).

The main aim of Day 2 of the field trip is that of illustrating and discussing the structure of the Lagonegro units in the high Agri River valley area. Excursion localities have been selected on the NNE side of the valley, where the relationships between Lagonegro units and the tectonically overlying carbonate platform units are particularly well exposed. Quaternary faulting and active tectonics of the high Agri River valley area will also be briefly addressed.

Locality 2.1: Monte Cugnone

In the area north of Monte Cugnone (or Monte Cognone; Fig. 2.2a) the main thrust fault within the Lagonegro units has been recognised by Scandone (1967, 1972). This structure (Marsico Nuovo Thrust in Mazzoli et al., 2001) produces the tectonic superposition of the Triassic Monte Facito Fm – or locally the Calcari con selce Fm – of the upper thrust sheet (Unità Lagonegrese II in Scandone, 1972) onto the Lower Cretaceous Galestri Fm of the lower thrust sheet (Unità Lagonegrese I in Scandone, 1972). The two superposed thrust sheets are characterised by different but clearly correlatable Upper Triassic to Lower Cretaceous stratigraphic successions (Scandone, 1967, 1972; cf. Pierfaone and San Nicola units in Mazzoli et al., 2001). Stratigraphic columns for the Mesozoic Lagonegro basin succession from different localities are shown in Fig. 2.3.

2.1a: Ginestole

In the area of C.se Ginestole (or Ginestre), a panoramic view of the tectonic superposition between the two previously mentioned Lagonegro thrust sheets can be taken. We shall be standing on Jurassic radiolarian cherts of the western limb of the Monte Cugnone anticline, a gently northwest-plunging, upright fold of about 1 km wavelength exposed in the footwall to the Marsico Nuovo Thrust (Fig. 2.2b-c). To the south, the latter thrust – down-thrown by an important WNW-ESE trending fault – crops out again east of the village of Marsico Nuovo (Fig. 2.2a). In the western part of the same down-faulted block, the tectonic superposition of shallow marine carbonates on top of Jurassic or Lower Cretaceous terms of the upper Lagonegro thrust sheet can also be observed (Fig. 2.2).

2.1b: Monte Cugnone quarry

We shall visit a large quarry located in the crestal region of the Monte Cugnone anticline. In this area, mostly characterized by sub-horizontal to gently dipping bedding, the upper part of the Upper Triassic Calcari con selce Fm and the Jurassic Scisti silicei Fm have been logged in detail (refer to Fig. 2.3). The well-bedded, fine-grained Upper Triassic limestones – containing chert layers, lenses and nodules – also host numerous arrays of en echelon tension gashes. These occur along shear zones of extensional type, which appear to have locally evolved to discrete normal faults (Mazzoli & Di Bucci, 2003; Mazzoli et al., in press; Fig. 2.4). Most of the en echelon vein arrays are arranged in conjugate sets, generally striking NE-SW and steeply
dipping (Fig. 2.5a). The veins belonging to the arrays are filled with calcite, and consist of a thick central portion that tapers off into narrow tails. In profile, veins are generally tens of centimetres in length and have maximum aperture width of a few centimetres. They mostly strike NE-SW and show steep angles of dip (Fig. 2.5b).

Early layer-parallel shortening (LPS) is documented by minor thrusting with associated outcrop-scale folding. Cross-cutting relationships demonstrate that LPS and flexural folding pre-dated the development of the en echelon vein arrays (Fig. 2.4f-g). Therefore, these structures can be best related to post-buckling extension roughly parallel to the regional, NW-SE trending, fold axis. Such a deformation seems to accommodate only a relatively low amount of strain, at least within this outcrop (where bulk extension is << 10%). The right-lateral reactivation of some fault planes (Fig. 2.5c) indicates that further horizontal compression (roughly E-W oriented) followed the development of our conjugate shear zones and associated faults.

Fluid inclusion microthermometry indicates that environmental (P-T) conditions remained constant during the different stages of vein array evolution and normal fault development. Maximum homogenisation temperatures from primary fluid inclusions from structures of different types (ranging from intact vein arrays to fully faulted ones) are all consistently in the range of 130°C-140°C (whereas secondary inclusions record Th values mostly ranging between 80°C and 115°C) (Fig. 2.6). In thin section (Fig. 2.7), vein calcite displays various degrees of twinning and undulose extinction: twin lamellae in the more intensely strained vein calcite consist of thick twins (Fig. 2.7a) generally organized in two, or rarely three, straight sets, and twins in twins. Lobate crystal margins indicate that dynamic recrystallization by grain boundary migration also occurred locally (Fig. 2.7b). Transgranular fractures and microcracks cutting though thick twins (mainly occurring adjacent to impingement zones between grains) are frequent and marked by secondary fluid inclusion trails (Fig. 2.7e). The occurrence of undulose extinction and twinning is indicative of crystal plastic deformation of the vein calcite, also testified by some grain boundary migration phenomena. However, the microstructure is characterized by a general lack of evidence for recovery (in the form of subgrain development or extensive dynamic recrystallisation), hence suggesting that temperatures were not high enough for dislocation creep to be important in these rocks. Low-temperature intracrystalline deformation dominated by glide processes alone (low-temperature plasticity) is likely to have led to strain hardening and to the widespread development of microfractures (Fig. 2.7c), thereby producing a switch to a dominantly brittle mechanical behaviour. According to Mazzoli & Di Bucci (2003) and Mazzoli et al. (in press), this change of mechanical behaviour would be essentially controlled by displacement accumulation along the vein arrays.

Locality 2.2: Agri River valley, national road n. 598, ca. km 35
We shall stop at a gas station located about 3 km west of Villa d’Agri for a panoramic view of the NNE side of the Agri River valley. The structure of the Lagonegro units exposed along the NNE valley flank includes several major, roughly N-S trending, faulted antiforms. The Monte Lama and Monte Volturino structures, which can be observed from this stop, consist of the Mesozoic succession of the San Nicola unit (Unità Lagonegrese I in Scandone, 1972; refer to Fig. 2.3). These major structures are locally bounded on their eastern and western sides by thrusts and backthrusts, respectively, and show a double vergence of associated fold structures (Fig. 2.8). The western major structure (Monte Lama) consists of a large box fold showing a vertical western limb (Fig. 2.8a), and a steep to overturned eastern limb offset by minor break-thrusts. East of it, the Monte Volturino structure also consists of a large antiform, showing a box fold geometry with a flat top. The western limb of this structure, down-faulted to the southwest, is back-thrusted over the Galestri Fm cropping out in the Torrente Molinara syncline (triangle zone; Figs. 2.9 and 2.10), whereas the overturned eastern limb links with an overturned, west-verging syncline (Fig. 2.8b).

Locality 2.3: Torrente Molinara – Serritello
Along the roughly N-S trending valley of the Torrente Molinara (Fig. 2.9), Lower Cretaceous, mostly pelitic rocks of the Galestri Fm crop out in the core of a syncline occurring between east-verging overturned folds and thrusts of Monte San Nicola – Monte Farneta (southern part of the Monte Lama major structure described above) and the west-verging kink fold of Monte Corno (a down-faulted portion of the Monte Volturino major structure).

2.3a: Road from Barricelle to Galaino, km 8
From locality 2.2 we shall drive a couple of kilometres to the SE along the main road (n. 598), then take the exit and drive toward Villa d’Agri, turning left toward Galaino. We shall stop along the road between Barricelle and Galaino, at km 8, to observe east-verging, asymmetric parasitic folds at Monte Farneta and the west-verging structure of Monte Corno, all involving the Calcari con selce and Scisti silicei Fms of the San Nicola unit (or Unità
**Locality 2.4: Monteto**

From the latter locality, we shall drive back to the SE towards Marsico Vetere, then take the road heading north towards Calvello. In the area of Bosco Volturino – Montetto – Scarrone Acqua di Bocca, we shall observe: (i) part of the stratigraphic succession (top of the Calcari con selce and Scisti silicei; refer to Fig. 2.3) of Monte Volturino (*San Nicola unit*), here steeply dipping to the east; and (ii) the tectonic superposition of rocks belonging to the two different types of Lagonegro successions observed in the previous locality occurs. The rocks lying in the footwall (i.e., to the west) belong to the *San Nicola unit*, whereas those in the hanging wall belong to the *Caldarosa unit* (refer to Fig. 2.3). The rocks exposed along the contact are those of the Lower Cretaceous Galestri Fm, in the footwall (*San Nicola unit*), whereas those in the hanging wall (*Caldarosa unit*) are progressively younger from south (Middle Triassic Monte Facito Fm) to north (Jurassic Scisti silicei, that we observed at locality 2.4). The whole structure is offset by a younger east verging thrust (previously mapped in Lazzari & Lentini, 1991; see Fig. 2.9). This produces tectonic reibrication (as it displaces the Monte Torrette Backthrust) and the superposition of hanging wall Mesozoic rocks on top of Miocene siliciclastics (Gorgoglione Fm) cropping out to the east (refer to Fig. 2.10).

**Locality 2.5: Monte Torrette**

We shall drive back from locality 2.4, stopping about 5 km south. Looking north, we shall observe the Monte Volturino – Monte Torrette area (Fig. 2.8c). The upright eastern limb of the Monte Volturino syncline, with its z-shaped parasitic folds, is truncated by a roughly N-S trending, east dipping hinterland-verging thrust (Monte Torrette Backthrust; refer to Fig. 2.10). Across this backthrust, the tectonic superposition of rocks belonging to the *Caldarosa unit* (refer to Fig. 2.3). The rocks exposed along the contact are those of the Lower Cretaceous Galestri Fm, in the footwall (*San Nicola unit*), whereas those in the hanging wall (*Caldarosa unit*) are progressively younger from south (Middle Triassic Monte Facito Fm) to north (Jurassic Scisti silicei, that we observed at locality 2.4). The whole structure is offset by a younger east verging thrust (previously mapped in Lazzari & Lentini, 1991; see Fig. 2.9). This produces tectonic reibrication (as it displaces the Monte Torrette Backthrust) and the superposition of hanging wall Mesozoic rocks on top of Miocene siliciclastics (Gorgoglione Fm) cropping out to the east (refer to Fig. 2.10).

**Locality 2.6: Rupe del Corvo – Monte S. Enoc (time permitting)**

At the junction located in the area of Vallone della Rocca, we shall take the road to Acqua dei Pastori – Viggiano, in order to observe the eastern major structures of the Lagonegro units exposed in the high Agri River Valley. These strucures (Rupe del Corvo and Monte Enoc anticlines; Fig. 2.11) involve the Lagonegro basin succession of the *Caldarosa unit* (or *Unità Lagonegrese II, facies Armizzone*, in Scandone, 1972).

**2.6a: Rupe del Corvo**

Stopping where the road crosses Torrente Alli, we can observe (looking north) the structure of Rupe del Corvo. This consists of a doubly-verging anticline cored by Calcari con selce, with a flat top and overturned western and eastern limbs (Fig. 2.11). The eastern fold limb links to an east-verging, overturned syncline, which is downfaulted with respect to the Monte Enoc structure farther east.

**2.6b: Monte S. Enoc**

From the junction immediately north of Viggiano, we shall take the road heading north (toward Laurenzana) along the eastern slope of Monte S. Enoc. The Monte Enoc structure consists of an east-verging overturned anticline (Fig. 2.11). This fold rests in the hanging wall to a thrust fault at whose footwall Miocene siliciclastic rocks (Gorgoglione Fm) are exposed (Fig. 2.8d). Part of the stratigraphic succession of the *Caldarosa unit* (refer to Fig. 2.3) as well minor structures (parasitic folds) associated with the major anticline can be observed along a dirty road climbing the eastern slope of Monte S. Enoc.

Parasitic folds to the Monte Enoc anticline, as well as to all major (first-order) features in the Mesozoic Lagonegro units of this area, include upright to recumbent (depending on the geometry of major structures), second-order folds of a few tens of metres wavelength (Fig. 2.8b), and upright to recumbent, third-order folds of metric size. In the latter, fold shape alternates between class 1 and class 3 of Ramsay (1967): competent limestone/chert layers have mostly rounded hinges and show class 1b or class 1c geometries, whereas less competent pelitic layers have angular to rounded hinges and typically exhibit class 3 geometries. Parasitic folds are of symmetric (m) type on the hinge zone of the main structures, whereas they display typical s and z
asymmetries on the limbs. Detailed structural analysis of the Lagonegro units exposed a few kilometres south of the study area indicates that folding initiated during a sinusoidal buckling episode predating thrust ramp development (Mazzoli, 1992). A dominant mechanical control on buckling at very low-grade conditions by the competent Upper Triassic limestones is suggested by the geometry of major folds (Mazzoli, 1992) and, in the high Agri River valley area, by the different characteristic wavelengths displayed by structures involving a thicker (San Nicola unit) or thinner (Caldarosa unit) Calcari con Selce Fm. The envisaged structural evolution would therefore be similar to that of break thrusts (Fischer et al., 1992), whereby both foreland- and hinterland-verging thrust ramps cut through the middle limbs of antiform-synform pairs (cf. fold-generated imbricates of Morley 1994).

It is worth noting that the envisaged structural evolution for this sector of the Agri River Valley does not put by any means into discussion the well-known occurrence of major thrusts – showing minimum displacements of few tens of kilometres (e.g. Scandone, 1972; Mazzoli, 1992) – within the Lagonegro units (the Marsico Nuovo Thrust in Fig. 2.2 being a clear example).

Locality 2.7: Villa d’Agri

From the latter locality, we shall drive along the northern flank of Val d’Agri heading west, toward Villa d’Agri, to observe a Quaternary fault system consisting of roughly N120° trending left-lateral strike-slip faults and associated features is exposed for a total length of about 15 Km (Cello et al., 2003 and references therein). The fault system includes (Fig. 2.12): (i) N020-N030 trending, right-lateral faults; (ii) N080-N100 trending, normal to left-lateral transtensional faults; and (iii) N130-N150 trending, left-lateral transpressional faults.

The main fault bounding the Val d’Agri basin to the north is exposed close to Villa d’Agri, for a length of about 3 km. Here, Pleistocene continental deposits are faulted in proximity of a roughly N120 left-lateral strike-slip fault, and fault rocks include 50-70 cm of cataclasites; the damage zone is about 100 m thick. The associated normal to left-lateral transtensional faults (oriented roughly E-W), show some 100-250 m of morphological displacement; they are characterized by a damage zone thickness of 20-40 m and by a cataclastic core of about 20-40 cm. A few tectonic depressions occur at those sites where the main fault attains a N080-N100 trend and a marked transtensional character (as in the area around Viggiano). On the contrary, positive features are associated with restraining bends along the fault, as it occurs at the northwestern edge of the area (near Galaino) where Lower and Middle Pleistocene continental deposits are folded in proximity of a N150 transpressional segment of a major strike-slip fault (Giano et al., 2000).

In the high Agri River Valley, Upper Pleistocene – Holocene slope deposits are locally displaced by ESE oriented strike-slip faults. This observation suggests a recent activity of at least part of the fault system. In particular, near Viggiano, slope deposits dated at 31,740 ± 970 years BP (Giano et al., 2000) are deformed within a fault zone with left-lateral transtensional kinematics trending roughly N110°.
References

Fig. 2.1. Geological sketch map of the high Agri River valley area (asterisks show location of stratigraphic logs in shallow marine carbonates analysed in Cello et al., 2002). X-X’ = trace of cross-section of Fig. 2.10. Y-Y’ = trace of cross-section of Fig. 2.11.
Fig. 2.2. (a) Geological map of the Monte Cugnone – Monte Calvelluzzo area.
Fig. 2.2. (b) Geological section across Monte Cugnone (legend as in Fig. 2.2c; located in Fig. 2.2a).

Fig. 2.2. (c) Geological section across Marsico Nuovo – Monte Calvelluzzo (located in Fig. 2.2a).
Fig. 2.3. Stratigraphic columns for the different Lagonegro units of the high Agri River valley and adjoining areas.
Fig. 2.3. cont.
Fig. 2.3. cont. Location (a) and stratigraphic columns (b-c) for the Volturino section.
Fig. 2.3. cont. Location (a) and stratigraphic column (b) for the Sellata section.
Legenda

- Argilliti silicifere rossastre e verdognole
- Radiolariti varicolori
- Calcarì e calcai marnosi fortemente silicizzati
- Calcilutiti grigie con liste e noduli di selce
- Calcarì dolomitizzati grigi con liste e noduli di selce
- Conglomerati intraformazionali

(a) Ubicazione della sezione-tipo “Fiumarella”;
(b) Colonna stratigrafica delle successioni affioranti.

Fig. 2.3. cont.
Fig. 2.3. cont.

(a) Ubicazione della sezione-tipo “Alli”; (b) Colonna stratigrafica delle successioni affioranti.
Fig. 2.3, cont.

(a) Ubicazione della sezione-tipo “Paterno”;
(b) Colonna stratigrafica delle successioni Affioranti nelle sezioni “Paterno” e “Padula”.

Tav. 199 II SE Marsico Vetere
Fig. 2.3. cont. Stratigraphic columns for the different Lagonegro units of the high Agri River valley and adjoining areas, showing gamma-ray logs obtained by field measurements.
Fig. 2.4. Examples of different types of structures exposed in the Monte Cugnone quarry. (a) Conjugate sets of vein arrays in the eastern quarry wall. (b) Line drawing from (a). (c) Intact, conjugate arrays of tensile cracks. Note deflection of bedding (arrowed). (d) Vein array showing incipient development of discontinuous shear-parallel fractures (arrowed) cutting across en echelon tensile cracks.
Fig. 2.4. cont. (e) Faulted shear zone, characterized by a continuous, discrete fault zone (arrowed) breaking through an original en echelon vein array. (f) En echelon vein array (E-W striking) cutting across fold-thrust structure. Note how vein array passes from thrust hanging wall to footwall without showing any displacement. Since angles in excess of 60° occur here between the quarry wall and the normal to the thrust transport direction, as well as between the strike of the vein array and the thrust transport direction, overprinting relationships are not just apparent. (g) Line drawing from (f).
Fig. 2.5. Orientation data for the Monte Cugnone quarry (lower hemisphere, equal area projection). (a) Poles to en echelon vein arrays (mean great circles for each of the two conjugate sets are shown, dipping 73° toward 310°N and 74° toward 129°N). (b) Poles to vein planes from en echelon arrays (mean great circles for the two dominant sets are shown, dipping 79° toward 305°N and 78° toward 127°N). (c) Discrete faults cutting through en echelon vein arrays (with slip vector determined from striae/shear fibres on fault plane; see text). (d) Poles to bedding (mean great circle shown, dipping 12° toward 264°N).
Fig. 2.6. Fluid inclusion data from vein calcite, Monte Cugnone quarry. (a) Cumulative melting temperature (Tm) data (P = primary inclusions; S = secondary inclusions). (b-e) Homogenization temperature (Th) data for different stages of vein array to normal fault evolution.
Fig. 2.7. Examples of microstructures from vein calcite, Monte Cugnone quarry. (a) Two sets of thick twins. (b) Lobate grain boundaries (suggesting dynamic recrystallisation by grain boundary migration processes) between calcite crystals. (c) Cracks with secondary inclusion trails (arrowed). (d) Iso-oriented primary inclusions (P) and straight microvein (MV) cutting through the crystals. (e) Primary fluid inclusion aligned along growth bands (arrowed). (f) Elongated two-phase primary inclusions (example arrowed). (g) Rounded two-phase secondary inclusions.
Fig. 2.8. Examples of outcropping structures involving the Lagonegro Basin rocks in the northern side of the high Agri Valley (TrM = Monte Facito Fm, TrU = Calcarì con selce Fm, J = Jurassic radiolarian cherts, KL = Galestri Fm; Mio = Middle-Upper Miocene turbidites). (a) West-verging anticlinal fold of Monte Lama (San Nicola unit). (b) East-verging overturned folds of Monte Volturino (San Nicola unit). (c) In the background: Monte Torrette Backthrust, involving different Lagonegro Basin successions in the hanging wall (Caldarosa unit) and footwall (San Nicola unit). In the foreground: down-faulted shallow marine (platf.) carbonates and tectonically underlying Lagonegro basin rocks (San Nicola unit, or Unità Lagonegrese I in Scandone, 1972) belonging to the eastern limb of the west-verging Monte Corno anticline. (d) East-verging overturned anticline of Monte Enoc (Caldarosa unit), overthrusting Miocene synorogenic strata to the east.
Fig. 2.9. Geological map of the Torrente Molinara – Serritello – Monte Volturino area.
Fig. 2.10. Geological section across the high Agri River Valley (located in Fig. 2.1).
Fig. 2.11. Geological section of Rupe del Corvo – M. S. Enoc (after Mazzoli et al., 2001; located in Fig. 2.1).
Fig. 2.12. Main Quaternary faults in the high Agri River Valley area (from Cello et al., 2003).