

INTRODUCTION

The reconstruction of thermal history of folded and thrust units is one of the main aims to define the pattern of tectonic loading and the time-space evolution of an orogen where tectonic exhumation processes occurred at shallow crustal levels. Nevertheless, in the external zone of fold-and-thrust belts, where levels of thermal evolution are generally low, it gets difficult to discriminate between the contribution to thermal maturity due to either tectonic or sedimentary burial. This is particularly true for sedimentary sequences deposited in basins characterized by highly variable subsidence rates such as syn-orogenic basins. Vitrinite reflectance ($R_o\%$), T_{max} , Kübler index (KI) and illite/smectite (I/S) and chlorite/smectite (C/S) mixed layers are parameters that have been widely used primarily in petroleum geology to correlate with stages of hydrocarbon generation and diagenesis, attained during the thermal/burial history in sedimentary basins and orogenic belts (Pollastro, 1993). Nevertheless, they may be affected by non diagenetic factors and show values that cannot be simply explained according to the burial and thermal history of the hosting sediments. They are highly sensitive in the 60-200 °C temperature range, and can help to reconstruct the thermal evolution of sedimentary successions, to estimate the orogenic shortening entities and to define the geometries and kinematics of the deformation. Furthermore, the definition of the thermal evolution of synorogenic deposits may be particularly significant for hydrocarbon exploration.

METHODS

We focused sampling on the the Laga Fm. (arenaceous, arenaceous-pelitic, pelitic-arenaceous and pelitic association of the Pre-evaporitic Member) developed to the west of the Montagna dei Fiori-Montagnone alignment where facies architecture, subsidence amounts, and tectonic loadings (now eroded) show a considerable variability along both strike and dip of the chain. Subordinately pre-orogenic succession (Marne con Cerrogna, Marne a Fucoidi and Rosso Ammonitico Fms.) was sampled in the structural culminations surrounding the basin (e.g., Montagna dei Fiori area).

Mean random vitrinite reflectance was measured on whole rock samples rich in coaly particles collected from sandstone, siltstone and clayey lithologies. Vitrinite reflectance analyses were performed on randomly oriented grains using a Zeiss Axioplan microscope and conventional microphotometric methods (e.g., under oil immersion in reflected monochromatic non-polarised light).

T_{max} , S1, S2 and S3 peaks were derived from standardised procedures of Rock Eval pyrolysis.

Quantitative analysis of the whole-rock composition and the <2 μm grain-size fraction was carried out with a Scintag X₁ XRD system (CuK α radiation, solid state detector) at 40 kV and 45 mA. Thermal parameters such as illite content in I/S mixed layers, and KI were determined by the decomposition of the XRD patterns using a profile-fitting method.

RESULTS

Vitrinite reflectance data

Analysed kerogene is generally abundant (coaly samples), homogeneous and mainly made up of well-preserved macerals. They mainly belong to the huminite-vitrinite group, with predominance of collotelinite and telinite fragments, and subordinately to the inertinite group. Pyrite either finely dispersed or in small globular aggregates is locally present along the rims of huminite-vitrinite macerals. Data show one main cluster identifying the possible autochthonous population of vitrinite-humite macerals. $R_o\%$ data indicate immature to early mature stages of hydrocarbon generation with slight differences in the study area.

Rock-Eval data

Selected Rock Eval data derive mainly from the Laga Fm. and, subordinately, from the Marne con Cerrogna and Bisciario Fms. S1 ranges between 0 and 0.11 mg/g; S2 between

0.25 and 2.64 mg/g; Tmax between 429-443°C; T.O.C. (Total Organic Content) between 0.51 and 4.62 wt%.

Tmax values correlate with immature to early mature and subordinately to middle mature stages of hydrocarbon generation, in reasonable agreement with Ro% data.

Mineralogical data

Pre-orogenic succession

The Marne con Cerroghna Fm. is characterized by illite, I/S, chlorite, kaolinite and non-clay minerals such as quartz, calcite and plagioclase. I/S are R0 structures in which the illite content is in the range of 48-50%. KI values ranges from 0.89 to 1.03 °Δ2θ and from 0.94 to 1.08 °Δ2θ in the ethylene glycol solvated and air-dried diffraction patterns respectively.

The Marne a Fucoidi Fm. is mainly composed of illite and I/S in which the smectite component is dominant. The calculated percentage of illite layers in I/S is of 40%. KI values are 1.01 and 1.08 °Δ2θ for the ethylene glycol solvated and air-dried oriented mounts respectively.

A slightly different mineral assemblage characterizes the Rosso Ammonitico Fm. Illite, I/S, chlorite and chlorite/smectite mixed layers (C/S) are the recognized clay minerals. Kaolinite is absent. I/S correspond to R1 structures with an illitic content of 64%. The Rosso Ammonitico Fm. records KI values of about 1.0-1.1 °Δ2θ similar to the overlain deposits.

Syn-orogenic succession

Analysis of randomly-oriented whole-rock powder patterns shows that shales and sandstones of the Laga Fm. are composed essentially of quartz, Na-plagioclase, dolomite, calcite, small amounts of K-feldspar and clay minerals. Pyrite, gypsum and gismondine are also recorded in few samples as minor phases. The <2 μm grain size fraction is composed mostly of illite, I/S, C/S, kaolinite and chlorite and subordinate non-clay minerals such as quartz, albite, calcite and gismondine. The pelitic-arenaceous lithology association shows mixed layered I/S with random stacking of layers in which the illitic content is about 50-52%. Ordered and disordered I/S were identified in the underlying arenaceous-pelitic lithology association. Only R1 I/S were recognized in the arenaceous lithology association.

The full width at half maximum heights expressed as KI is variable. The experimental widths range from 0.37 to ~ 1.0 °Δ2θ in the air-dried specimen and from 0.34 to 0.84 °Δ2θ in the ethylene glycol solvated oriented mounts.

TENTATIVE PALEOTEMPERATURE CONVERSION AND ESTIMATED MAXIMUM BURIAL

To relate KI data and the percentage of illite layers in I/S to maximum paleo-temperatures and to the other organic thermal indicators, we adopted the basin maturity chart proposed by Merriman and Frey (1999). To properly convert Ro,% data into paleotemperature we used the equations proposed by Barker and Pawlewicz (1994).

Based on mixed layer clays and their stacking order, the Laga Fm. and the underlying pre-orogenic succession experienced maximum paleotemperatures lower than 100-110 °C (Fig.1a). This is in agreement with the presence of C/S mixed layers which first appearance in diagenesis is generally associated with temperatures of 60-160°C. On the contrary, KI data greatly overestimate paleotemperatures calculated for the Laga Fm. They primarily refer to detrital micas inherited from the uplift of the Alpine-Appennines chain.

Moving from sector 1 to 6, approximately from the W to the E, KI-derived paleotemperature ranges approach those calculated by I/S mixed layers.

In Fig.1b, we list the calculated maximum burial (in blue) and the stratigraphic thickness (Fig.2) of the Laga Fm. to the top of the evaporitic member (in yellow).

Loads were calculated assuming a pre-erosional geothermal gradient of 22°C/km and a surface temperature of 10°C. Estimated burials range from <2.0 to 4.0 km with highest values in the depocentre of the basin and the lowest to the north of the studied area (sector 5). Local anomalies are recorded at the footwall of regional thrusts.

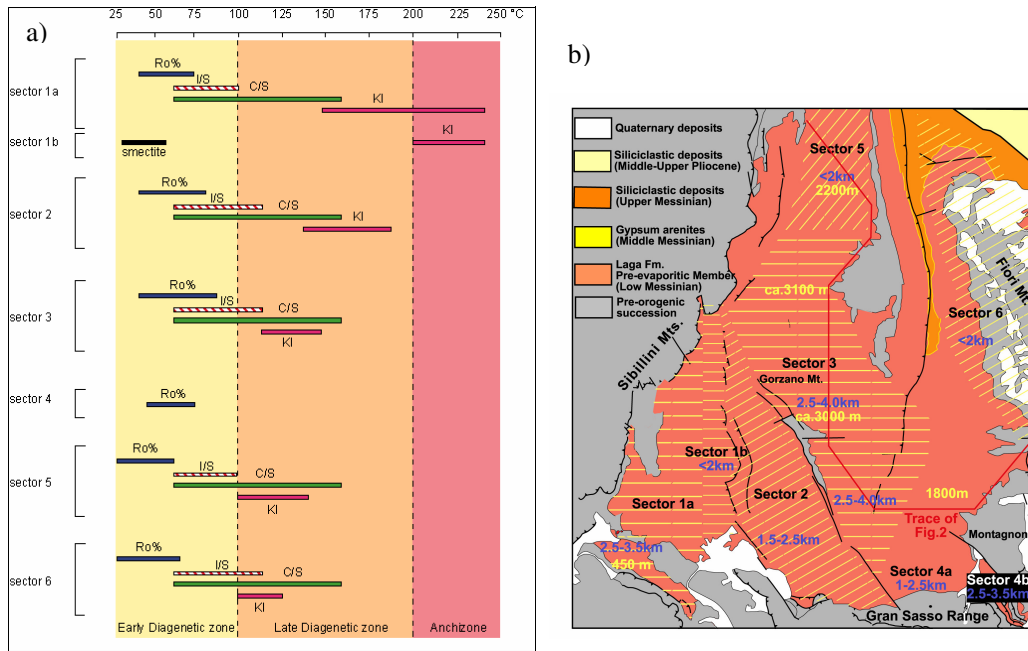


Fig. 1a - Basin maturity chart showing correlation of clay minerals geothermometers with $R_o\%$; b) Sketch map of the Laga Basin showing calculated maximum burial (sedimentary and/or tectonic, in blue) and the stratigraphic thickness of the Laga Fm. to the base of the pre- evaporitic member (in yellow). Sectors indicate areas with analogous structural evolution.

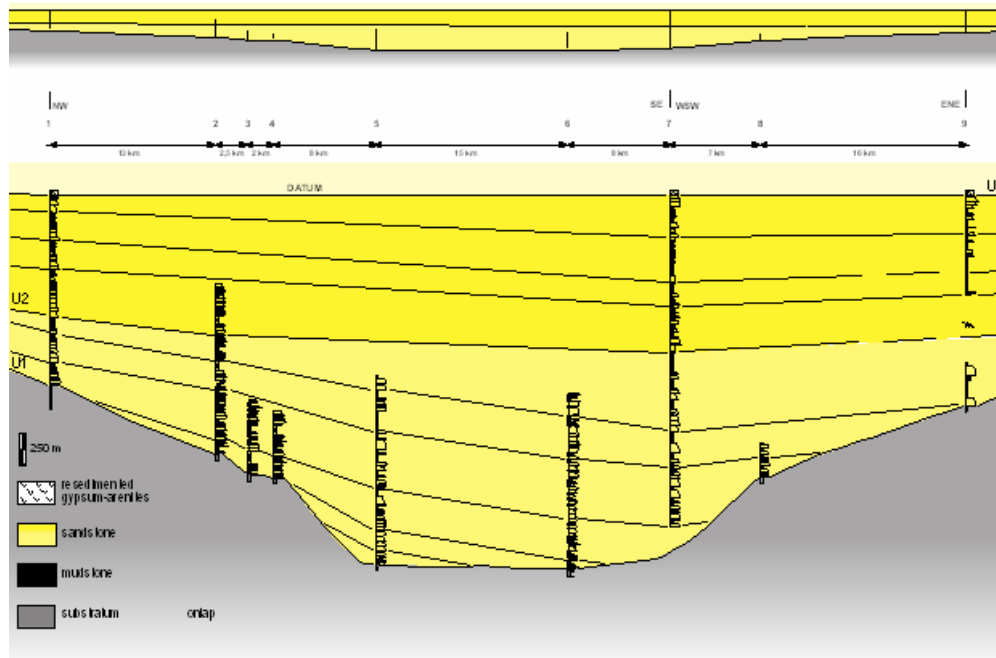


Fig. 2 - Correlation panel showing the deformed turbidite foredeep succession of the Lower Messinian Laga Formation (after Milli et al. 2004).

DISCUSSION

Estimated burials based on clay mineralogy in the Lower Messinian depocentre located between Gorzano Mt. and Vomano R. range from about 2.2 to 4.0 km and generally agree with measured $R_o\%$ data. Moving to the north in Uscerno area, available $R_o\%$ data indicate a maximum burial of about 1.3-1.6 km in a general agreement with measured stratigraphic

thicknesses of about 1.4-2.5 Km. Local anomalies are recorded at the footwall of regional Sibillini and Gran Sasso Thrust fronts. At the footwall of the Sibillini Thrust, in Borbona area, the proposed stratigraphic thickness of Laga fill varies between 1.0 and 1.5 km while maximum burials higher than 2.0 km were estimated on the base of either C/S and random I/S coexistence or not oxidised $R_o\%$ values between about 0.45 and 0.50%. Thus it seems realistic that this area subdued the thermal imprinting of the nowadays eroded Sibillini thrust. In front of the Gran Sasso structure, no complete reconstruction of the sedimentary thicknesses of the Laga Depositional Sequence is available. Nevertheless, we observe that to the north of Corvo Mt. (western Gran Sasso front) $R_o\%$ values for the arenaceous lithology association indicate the immature stage of hydrocarbon generation with maximum calculated burials of less than 1.5 km, while to the north of the Corno Grande thrust fault for the pelitic lithology association, $R_o\%$ values indicate the base of the oil window, about 0.5%, with maximum calculated burials of about 2.5 km. This implies that the Gran Sasso front loses displacement moving from the East to the West as already shown by D'Agostino et al. (1998). Low values for the Montagna dei Fiori pre-orogenic succession are indicative of scarce syn-orogenic sedimentary burial mainly represented by the preserved Meso-cenozoic pre-orogenic succession itself. It is in a general agreement with fluid inclusion data from the base of the Montagna dei Fiori pre-orogenic succession (Calcare massiccio Fm.). In this unit, homogenisation temperatures (T_h) are between about 70-90°C due to the maximum sedimentary burial occurred in middle Miocene times and between about 110-130°C due to both hot fluid circulation and sedimentary burial in Upper Miocene times (Ronchi et al. 2003). Further regional studies based on apatite fission tracks and $R_o\%$ on the Laga Basin were lately performed (Rusciadelli et al. 2005). They suggest for the Laga Fm. to the west of the Montagnone-Montagna dei Fiori alignment, maximum paleo-temperatures ranging between 50-110°C, in agreement with those proposed in the present study.

CONCLUSIONS

The acquired thermal maturity of the Laga Fm. is mainly due to sedimentary burial not exceeding 4.0 kilometres in the basin depocentre. A progressively thickness reduction up to about 1.5 km toward the North reflects the articulated basin physiography in Lower Messinian times. Data range from early mature (and subordinately mid-mature) to immature when compared to stages of hydrocarbon generation. Slightly higher level of diagenesis are recorded at the footwall of regional thrust sheets.

REFERENCES

- Barker, C.E. and Pawlewicz, M.J. [1994] Calculation of vitrinite reflectance from thermal histories and peak temperatures. A comparison of methods. In: Mukhopadhyay, P.K. and Dow, W.G. (Eds.). *Vitrinite reflectance as a maturity parameter: applications and limitations*. ACS Symposium Series, **570**, 216-229.
- D'Agostino, N., Chamot-Rooke, N., Funicello, R., Jolivet, L. and Speranza, F. [1998] The role of pre-existing thrust faults and topography on the styles of extension in the Gran Sasso Range (Italy), *Tectonophysics*, **292**, 229-254.
- Merriman, R.J. and Frey, M. [1999] Patterns of very low-grade metamorphism in metapelitic rocks. In: Frey, M. and Robinson, D. (Eds.) *Low grade metamorphism*. Blackwell, Oxford, 61-107.
- Pollastro, R.M. [1993] Consideration and applications of the illite/smectite geothermometer in hydrocarbon-bearing rocks of Miocene to Mississippian age. *Clays and Clay Minerals*, **41**, 119-133.
- Ronchi, P., Casaglia, F. and Ceriani, A. [2003] The multiphase dolomitization of the Liassic Calcare Massiccio e Corniola successions (Montagna dei Fiori, Northern Apennines, Italy). *Bollettino della Società Geologica Italiana*, **122**, 157-172.
- Rusciadelli G., Viandante, M.G., Calamita, F. and Cook, A.C. [2005] Burial-exhumation history of the central Apennines (Italy), from the foreland to the chain building: thermochronological and geological data. *Terra Nova*, **17** (6), 560-572.