Palaeontologia Electronica
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THE AMOUNT OF THE TAPHONOMIC/TECTONIC COMPACTION IN THE FLUMINIMAGGIORE FORMATION (SW SARDINIA, ITALY) WITH DISCUSSION OF A NEW PALEONTOLOGICAL METHOD FOR ESTIMATING COMPACTION

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ABSTRACT

By means of new method for geometrically reconstructing the thicknesses of original nautiloid shells (described herein), an estimate of the taphonomic-tectonic compaction of the Fluminimaggiore Formation (south-western Sardinia) is obtained.

KEY WORDS: Taphonomy, compaction, nautiloid cephalopod geometry, sedimentary calcareous body, chord of an arc, Fluminimaggiore Formation, Silurian, SW Sardinia, Italy.

Submission: 20 September 2001 Acceptance: 19 November 2001

INTRODUCTION

The so-called '**Orthoceras** Limestones' of the Fluminimaggiore Formation (southwestern Sardinia) have been known since the last half of 19^{th} Century (Meneghini, 1857 in La Marmora; Bornemann, 1881; Zoppi, 1888; Canavari, 1899). The paleontology and sedimentology of these units have continued to be investigated to the present day (Taricco, 1921; Novarese and Taricco, 1922; Teichmüller, 1933; Serpagli and Gnoli, 1977; Gnoli et al., 1979 and Ferretti et al., 1998). Despite these studies, our knowledge of the spatial geometry of these Lower Palaeozoic sedimentary bodies remains scant, especially with respect to their thicknesses. This situation results from the strong tectonic deformations (linked to the Caledonian then the Hercynian orogenies) that have complicated the sedimentary strata of southwestern Sardinia. Interestingly, paleontological analyses may provide aspects of a solution to unravelling the structural geology of these units. This paper presents a geometrical analysis of deformed orthoconic nautiloid shells previously described by Gnoli et al. (1990) and Ferretti et al. (1998) whose purpose is to estimate the amount of the thickness reduction in this Sardinian sedimentary sequence resulting from post-depositional compaction and structural deformation.

THE ORTHOCERATITE LIMESTONE

The Orthoceratite Limestone of south-western Sardinia clearly suffered compaction after the deposition. Furthermore, the tectonic stresses applied to this region during the Caledonian and Hercynian orogenies further deformed these originally stratified sedimentary deposits to the extent that this

Gnoli, Maurizo. 2002. The Amount of the Taphonomic/Tectonic Compaction in the Fluminimaggiore Formation (Sw Sardinia, Italy) with Discussion of a New Paleontological Method for Estimating Compaction. **Palaeontologia Electronica** 4(2):6pp, 709KB;
http://palaeo-electronica.org/paleo/2001_2/compact/issue2_01.htm

rock body now forms a series of rounded-edge, lens-shaped structures (Fig. 1) with a maximum thickness of several decimetres. Gnoli et al (1979, p. 408, Fig. 2) demonstrated that these bodies clearly preserved fine horizontal 'plane-parallel' laminations of the original sediment, abruptly interrupted at the edges of each 'lens'. The rounding of these lenses could be due either to weathering or to tectonic lamination. There is also a possibility that aspects of these 'lenses' formed as a result of deposition on an undulating sea bottom and that this original geometry was later accentuated by the tectonic deformation.

While several classic analyses of compaction of sedimentary limestone bodies are well known (e. g. Meyers 1980 and references therein), these have not taken advantage of the information to be gained by geometrical studies of associated fossil deformations. To correctly estimate the amount of post-depositional thickness reduction experienced by these deposits, a reference datum derived from an original synsedimentary geometry is required. Reference geometries of this type can be obtained from these Sardinian deposits via analysis of the fossil orthoconic cephalopod visors and body chambers that occur in these sediments in coquina-like profusion (Serpagli and Gnoli, 1977; Gnoli, 1987, 1990, 1994, 1996; Gnoli and Kiselev, 1995).

In order to precisely define the age of the examined faunas, a small sample was processed for conodonts, using the conventional acetic-acid technique (Stone 1987). The conodont fauna is very rich (over 250 elements/kg) and well preserved. In addition, a few phyllocarid gnathal lobes have been recovered. Recovered conodont elements belong to **Kockelella variabilis variabilis, K. v. ichnusae, K. absidata absidata, Ozarkodina excavata excavata** and **Oz. exc. inflata.** Based on this fauna, the sample can be dated as the upper Gorstian in terms of the Sardinian Conodont Zonation (Corradini and Serpagli, 1999), and referred to the *Oz.* **exc. hamata** Zone or to the lower part of the **A. ploeckensis** Zone.

Figure 1. Picture of a lens-shaped "**Orthoceras**" Limestone body inside the Fluminimaggiore Formation labeled in the field as SF 11 overlying a clearly stratified fossiliferous limestone. Fluminimaggiore Path Section.

Figure 2. Picture of a polished "**Orthoceras**" limestone slab from the Fluminimaggiore Fm. bearing the cross-section of a nautiloid living chamber showing clastic and partially plastic deformation by compaction. Cutting plane oriented perpendicular to bedding plane. x 1.5

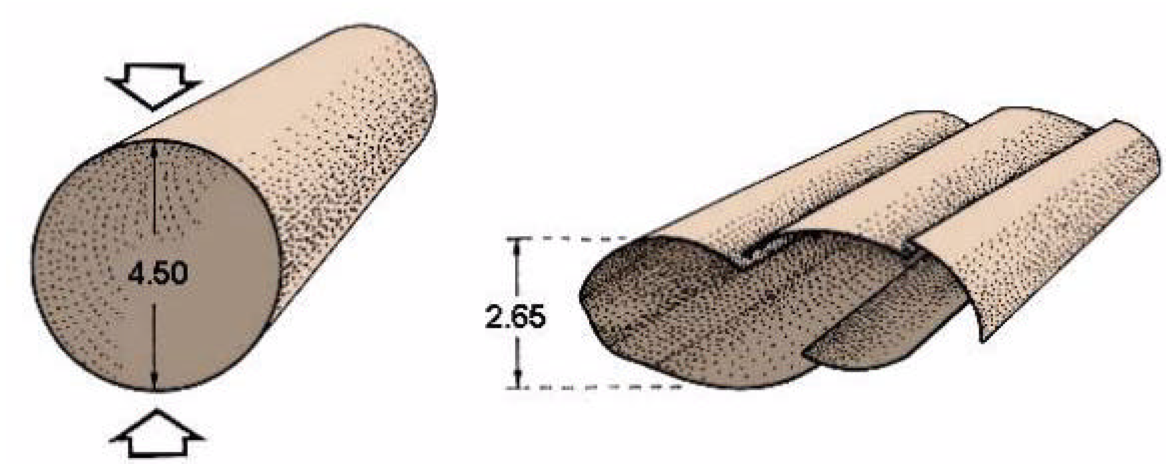

Figure 3. Dimensional relationship between orthoconic nautiloid conical body-chamber fragments which are able to be measured in the selected sample and its reconstruction to the original (presumably) circular geometry before compaction events (measurements in centimetres). Graphics by Mr. G. Leonardi.

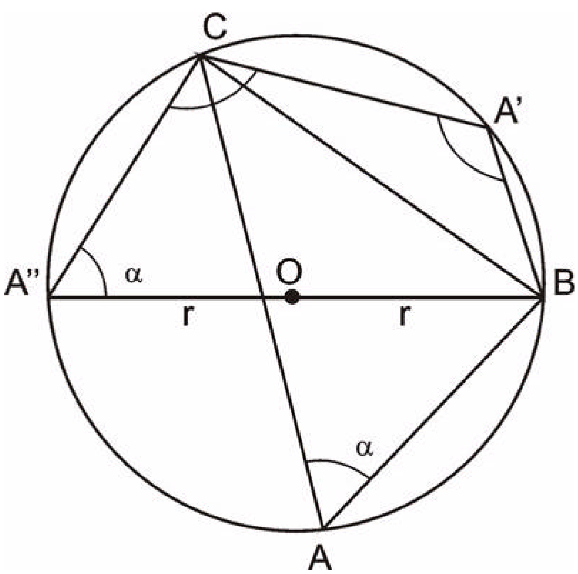

Figure 4. Geometry of circular arc segments. See text for discussion.

METHODOLOGY

The crushing of the cephalopod fossils is mostly a clastic deformation transforming their original circular geometry in an overlapping of conical fragments in the same way as some house-roofing tiles (Figure 2 and Figure 3). Provided one can assume that the orthocone shell was deformed from an initially circular cross-section, the Chord of the Arc of Conjecture Method can be used to estimate the radius of the original circle from measurements obtained from arc segments.

Given a circle (Fig. 4) of radius *r* and its center at *O,* two randomly chosen points along its circumference (*B* and *C*) define an arc-segment whose basal chord is $\overline{BC}$. It is now possible to draw a line from *B* through the origin (*O*) so we can obtain the position of point *A*'' which represents the third vertex of the right triangle *CA''B* that subtends the chord $\overline{BC}$. Let us call the magnitude of the angle represented by this vertex α. From these geometric relations it follows that $\overline{BC} = 2r\sin\alpha$.

If we now consider a point (*A'*) between points *B* and *C* such that *BA''CA'* forms a quadrilateral, we may infer the magnitude of the angle BA'C as $\pi - \alpha$ because of the fact that every quadrilateral inscribed in a circle has supplementary opposite angles. Thus, in every circumference of centre *O* and radius *r,* the length of a chord is equal to the length of the diameter multiplied by the sine of the angle that subtends the chord. This, in turn, means that information sufficient to estimate radius of any circle is contained in the geometry of any arc segment.

Using appropriate geometrical analyses (see Fig. 5) it is possible to estimate this radius using either angular or linear data (Fig. 5A and Fig. 5B respectively). In most cases, however, it will be best to base the final estimate on the average radius estimates from sets of arcs rather than relying on single calculations. Once these estimates have been obtained, comparison between the estimated diameter of the body chamber with the thickness of that preserved in the sediment (Fig. 6) will yield an approximate value of the lithological unit's taphonomic-tectonic compaction.

AN EXAMPLE CALCULATION

In order to illustrate the estimation of an orthocone radius from a fractured segment, consider the following scenario. Given a crushed shell segment

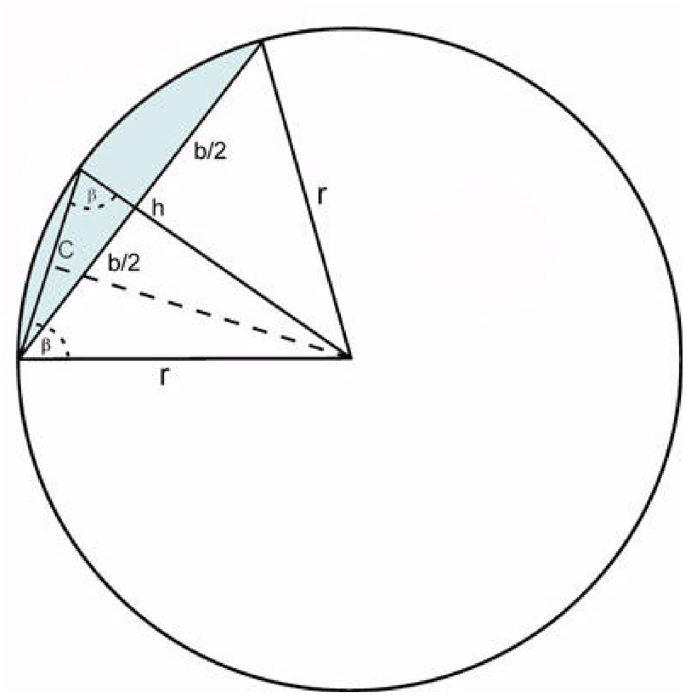

Figure 5. Formulas for geometrical estimation of a circle's radius (r) from measurements of arc segments. **A.** Trigonometric angular-function calculations. **B.** Linear-distance calculations.

A.

$$\tan\beta = \frac{b/2}{h}$$

$$\beta = \arctan\left(\frac{b}{2h}\right)$$

$$c = \sqrt{(b/2)^2 + (h)^2}$$

$$r = \frac{c/2}{\cos\beta} = \frac{c}{2\cos\beta} = \frac{\sqrt{(b/2)^2}}{2\cos(\arctan {}^{b}/_{2h})}$$

B.

$$c = \sqrt{(b/2)^2 + (h)^2}$$

$$\cos\beta = \frac{h}{c}$$

$$r = \frac{c/2}{\cos\beta} = \frac{c/2}{h/c} = \frac{c^2}{2h}$$

$$r = \frac{(b/2)^2 + (h)^2}{2h}$$

with a linear length of 47 mm and a height 16 mm, the third side of the right triangle (= b/2 of Fig. 5B) is 44.193 mm (via Pythagorus' Theorem). Once these three values have been obtained, the radius of the circle that includes the fractured shell segment can be estimated from the series of equations in Figure 5B as:

$$r = \frac{(b/2)^2 + h^2}{2h}$$

$$r = \frac{42.38^2 + 14.0^2}{28.0}$$

$$r = \frac{1992.07}{28}$$

$$r = 71.15$$

RESULTS

Inside the Orthoceratite limestone lithology of the Fluminimaggiore Formation, the nautiloid shell size variability is very high, with the maximum diameter (at the peristome) varying from few millimetres to 10.0 cm. The average diameter of the nautiloid shells tested by measurement of a dozen clastically deformed, transversally sectioned fragments, is 4.5 cm. Comparison of this datum with the thickness of specimens now preserved in the rock—after the various tectonic-diagenetic events (due to clastic and partially plastic deformation)—gives a thickness of 59 per cent. Based on these estimates, the reduction in thickness of the calcareous units bearing nautiloids is approximately 41per cent. It should be remembered that this compaction value is not a value for the interbedded clastic units that also occur within this formation. Separate analyses of fossils from these clastic units would be necessary in order to estimate their compaction ratio. Nevertheless, it is unlikely that the overall compaction ratio for the Fluminimaggiore Formation as a whole is less than 41per cent.

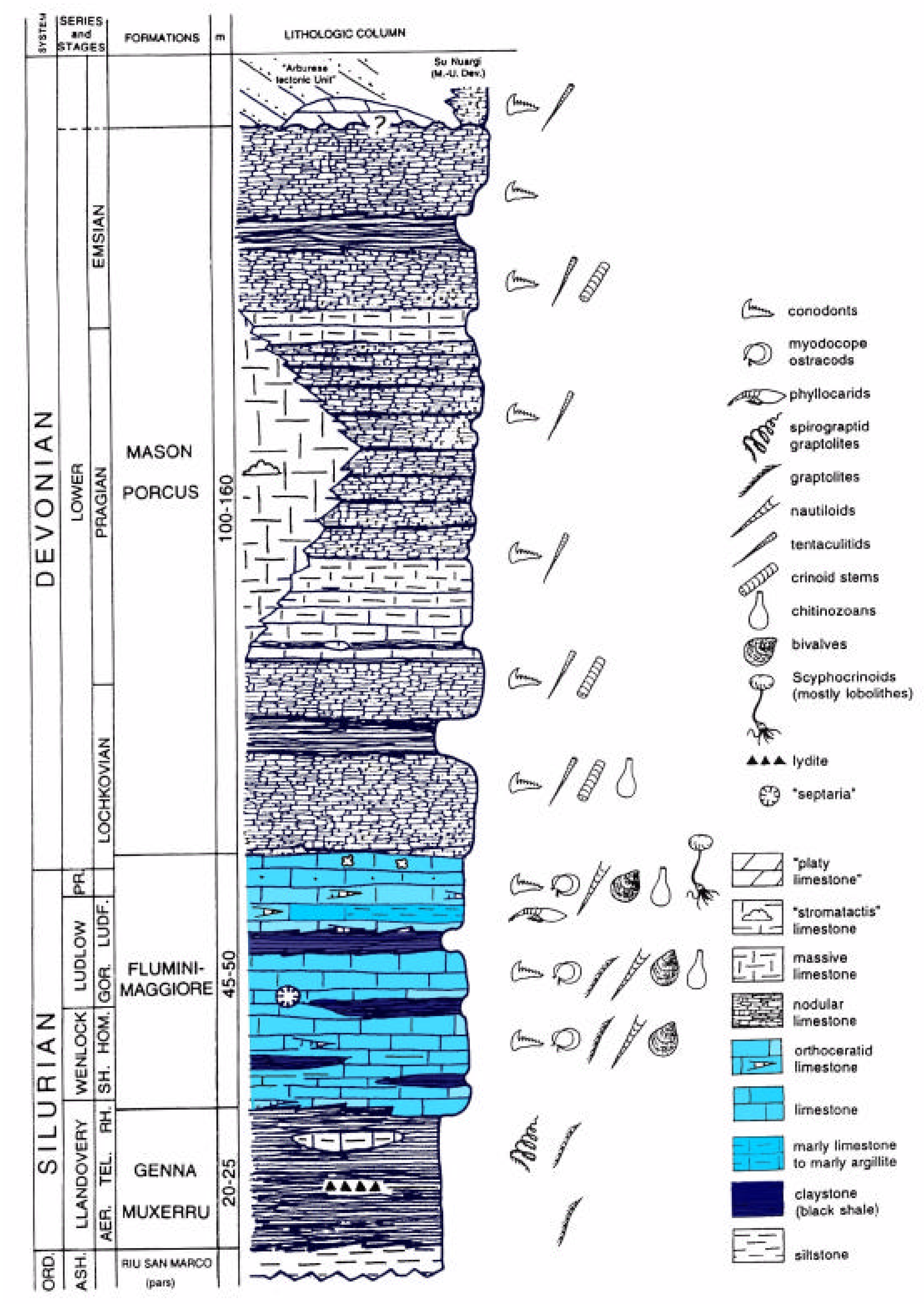

Figure 6. Relationships between the various lithologies of the Silurian-Lower Devonian of SW Sardinia (after Ferretti et al., 1998).

Indeed, the last estimated thickness of the Fluminimaggiore Formation is 45-50 metres (Ferretti et al, 1998). Based on our new compaction results, it seems likely that the unit's original (pre-compaction) thickness was on the order of 70 metres.

CONCLUSIONS

The procedure described above could be useful for any nautiloid-bearing rock body. In this context it is interesting to note that the Orthoceratite limestone facies represents one of the most common and widespread lithologies of the Early Palaeozoic (Holland et al, 1994).

ACKNOWLEDGEMENTS

I acknowledge Dr. F. Gorrieri for useful suggestions and advice, Prof. G. Facchinetti who checked the mathematical part of the study, Carlo Corradini who supplied the biostratigraphy, and the efforts of two anonymous reviewers whose comments improve the manuscript. I also acknowledge Dr. Norman MacLeod for improvement of my English. MURST and CNR grants (resp. Prof. E. Serpagli) provided funding for this research.

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