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Interacting lithogenesis and pressure-solution deformation in conglomerates: example from the Aliaga basin (Iberian Chain)

Interacción entre litogénesis y deformación por presión-disolución en conglomerados: ejemplo de la cuenca de Aliaga (Cordillera Ibérica)

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ABSTRACT

In conglomerates made of soluble components, much deformation uses to be accommodated by pressure solution. This mechanism can result in strong volume reduction, as well as in lithological (textural and compositional) changes owing to selective dissolution of rock components, and development of anisotropic fabrics. We study an example of Cenozoic conglomerates deformed by Alpine compression in the Aliaga basin (Iberian Chain). Active pressure-solution was favoured by (i) high solubility of limestone pebbles in relation to matrix silicic grains, (ii) probable low strain rate, (iii) presence of early cementation. Low relative mobility between matrix grains prevents them from free-flowing around pebbles; instead, the ensemble matrix-cement behaved as a rigid flow unit, its interface with a soluble pebble becoming a single stylolitic surface. Solution lineations tend to be consistently parallel to each other and parallel to the maximum shortening/compression axis, which results in net volume reduction.

Key-words: *Pressure-solution, shortening, cementation, solution lineation.*

RESUMEN

En conglomerados formados por componentes solubles, buena parte de la deformación suele ser acomodada por presión-disolución. Este mecanismo produce reducción de volumen y cambios litológicos (texturales y composicionales) debido a disolución selectiva y desarrollo de fábricas anisótropas. Estudiamos un ejemplo de conglomerados cenozoicos en la cuenca de Aliaga (Cordillera Ibérica), donde la presión-disolución fue favorecida por (i) alta solubilidad de los cantos de caliza respecto a los granos silíceos de la matriz, (ii) baja tasa de deformación, (iii) presencia de cementación temprana. La baja movilidad relativa de los granos de la matriz les impide fluir libremente alrededor de los cantos; por el contrario, el conjunto matriz-cemento se comporta como una unidad de flujo rígida, y su interfaz con el canto soluble, en una superficie estilolítica simple. Las lineaciones de disolución tienden a mantenerse paralelas entre sí y al eje de máximo acortamiento y máxima compresión, lo que produce reducción neta de volumen.

Palabras clave: *Presión-disolución, acortamiento, cementación, lineación de disolución.*

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Introduction

Conglomerates are granular materials that, under tectonic stress, show a rheological behaviour different from that of 'continuous' rocks. In particular, in conglomerates made of soluble components (e.g. limestone) embedded in a silicic matrix, much deformation is accommodated by a pervasive viscous deformation mechanism: pressure solution. Since no stress threshold exists for the process to start, pressure-solution structures can develop at stress levels much lower than those required for tension or shear failure (Durney, 1972).

Pressure solution produces distinct imprints on pebble surfaces:

(a) Circular to elliptic centimetre-scale concavities at contact points between pebbles (pitted pebbles). Relative solubility and curvature of pebbels are critical factors that determine the final geometry: at each contact, the less soluble and/or the most curved pebble tends to penetrate into the neighbour, while pebbles showing similar solubility and curvature tend to maintain nearly plane contacts (Trurnit, 1968). This results in progressive change of pebble shape and development of dimensional anisotropic fabric.

(b) Narrow (usually milimetre-scale wideness) pits and lineations, produced by indentation of non-soluble, mainly silicic grains of the matrix. These usually show a *radial pattern* covering wide portions of the curved surface, with typical zonation around two poles of maximum dissolution with orthogonal or high-angle solution pits (Estévez and Sanz de Galdeano, 1983; Hippolyte, 2001).

The complete process, including dissolution of soluble components, diffusion or solution transfer, and precipitation, can finally result in strong volume reduction and subsequent lithological changes:

(a) Precipitation in neighbouring pores or veins (closed system) involves: (i) volume loss without mass loss, hence the existence of a limit for the process to work (linked to the original porosity); (ii) conservation of the overall composition of rock.

(b) Precipitation in veins or sedimentary bodies far away (open system) involves (i) both volume and mass loss with no virtual limit; (ii) change in rock composition owing to selective dissolution, hence enrichment in less-soluble components.

In this paper, we study an example of Cenozoic conglomerates deformed by compressional tectonics in the Aliaga basin (Iberian Chain), showing the imprint of pressure-solution under tectonic stresses, approaching magnitude of strain, and illustrating the dependence of deformation patterns on coeval lithification processes.

Geological setting

The Aliaga basin is an intramontane piggy-back basin located on the Utrillas thrust sheet (Fig. 1). Six units (T1 to T6, early Eocene to middle Miocene in age) have been distinguished within the sedimentary infill (González and Guimerà, 1993). The basin is divided into two sectors by the Campos-Aliaga anticline; Paleogene units mainly occupy the eastern sector while Neogene units are restricted to the western one. Carbonatic conglomerates deposited in proximal and intermediate domains of alluvial fans are abundant in units T2 to T6, usually made of rounded to subrounded pebbles embedded in a silicic sand matrix (Fig. 2A).

Both the Mesozoic cover and the Cenozoic units were strongly folded during transport of the thrust sheet, under multiple compressions oriented ESE-WNW, ENE-WSW, NNW-SSE and NNE-SSW (Simón, 2006). Two main fold sets (trending NNW-SSE and ENE-WSW, respectively) can be distinguished, mostly coeval with Cenozoic units and showing a variety of superposition structures of ENE-WSW folds on NNW-SSE ones (Simón, 2004). In contrast, faults are almost absent in Cenozoic units (except for the major ENE-WSW thrust making the southern margin of the western sector), which reveals that conglomerates behave as a long-term ductile material under tectonic compression.

Nevertheless, this does not mean that conglomerates behaved as a granular non-cohesive material. Microscopic analysis reveals the occurrence of early cementation of the silicic matrix (by e.g. edaphic micrite or vadose silt; Fig. 2B), so not very long after burial and, very probably, prior to deformation. Only a small fraction of later sparitic cement is found, probably originated by precipitation, in the remaining pores, of carbonate dissolved by tectonic pressure.

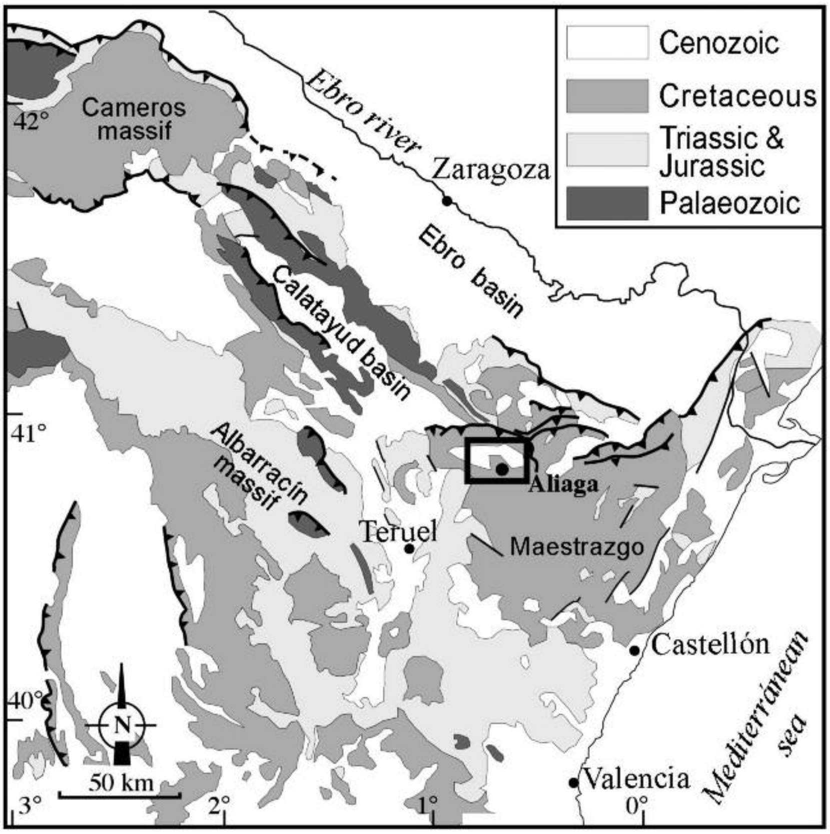

Fig. 1.- Location of the studied area within the NE Iberian Chain.

Fig.1.- Situación del área de estudio en el NE de la Cordillera Ibérica.

A scenario with multiple deformation mechanisms

Apart from folding at a macrostructural scale, as described above, the conglomerates of the Cenozoic Aliaga basin have recorded three internal deformation processes: (1) c*ompaction by re-arranging and clast rotation*, (2) *pressure-solution*, and, very rarely, (3) *fracturing.*

All these mechanisms could be considered within the following scenario of progressive deformation:

(1) First, nearly spherical grains in open-packing clastic rocks will be able to roll along each other allowing overall viscous deformation. Since packing becomes closer, reduction of external volume occurs; in the case of well-selected sands, a reduction of the porosity from 40% to 26% (therefore net volume reduction up to 14%) was estimated by Houseknecht (1987), which could also be applied to well-rounded and well-selected gravel. Any further reduction should be accomplished by plastic grain deformation or mass transfer.

(2) Once pebble-supported gravel acquires compact packing (or the conglomerate becomes well-cemented), both rotation and translation could be blocked. Deformation is then controlled by stress transmission through pebble contacts (Gallagher *et al.*, 1974). If deformation rate is low or solubility of pebbles is high, shortening can be full accommodated by pressure solution, therefore producing additional volume reduction whose virtual limit is the proportion of soluble components within the rock.

(3) On the contrary, if deformation rate is high or solubility of pebbles is low, stress concentration on contacts can produce tension fractures that propagate from such points into the pebbles (Gallagher *et al.*, 1974; McEwen, 1981).

In the case of conglomerates of the Aliaga basin, the importance of mechanical packing has been assessed by means of analysis of 2D images taken on flat field exposures. Samples of conglomerates with no visible evidence of dissolution at pebble surfaces were selected for this purpose. The re-

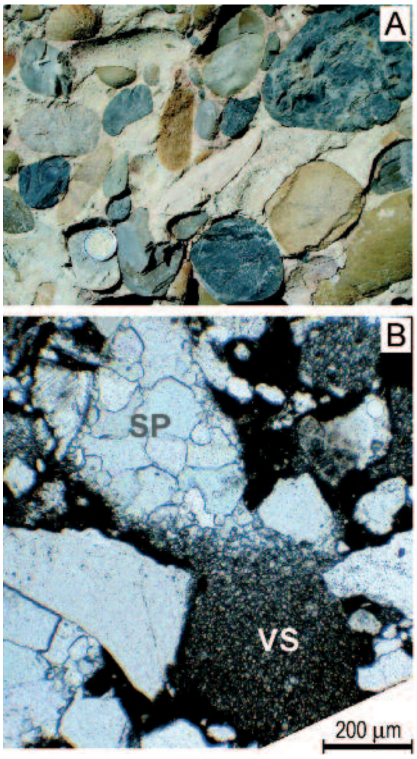

Fig. 2. A) Field example of carbonatic conglomerates of unit T5. B) Microscopic view of a T5 conglomerate showing early cementation: microkarstic cavity infilled with vadose silt (VS) overlayed by younger sparite (SP).

Fig. 2. A) Ejemplo de conglomerados calcáreos de la unidad T5. B) Imagen microscópica de un conglomerado (unidad T5) con cementación temprana: cavidad microkárstica rellena de limo vadoso(VS) y esparita más reciente (SP).

sults indicate that pebbles represent 60-70% of the total volume of the rock in six samples of unit T5 (early Miocene), and about 75% in two samples of unit T3 (early Oligocene). These values indicate a moderate to high degree of packing (higher in the case of older conglomerates) that was probably acquired by compaction under lithostatic load.

After attaining such compact packing, pressure solution became the dominant deformation mechanism, as evidenced by (i) abundant solution lineations produced by quartz grains of the matrix incising pebble surfaces, which show directions compatible with distinct tectonic compressional stress fields (Simón, 2006), and (ii) indentation between pebbles. In contrast, tension (Mode I) fractures propagated from contact points between pebbles, and shear (Mode II) fractures propagated through pebble/matrix interfaces are very scarce. This reveals that, during tectonic deformation, conglomerates of the Aliaga basin essentially behaved as a ductile material.

Kinematical patterns of pressure solution conditioned by rheology and lithogenesis

Deformation marks produced by indentation of non-soluble matrix grains into the surface of soluble pebbles include a continuous morphological transition between stylolites, slickolites and striations *s.s.*, with a common pressure-solution origin that makes it advisable to adopt for them a common genetic term: *solution lineations*. The latter record flow trajectories of insoluble matrix grains, showing a continuous range of deformation patterns according to the bulk strain ellipsoid (Simón, 2007).

A noticeable tendency to parallelism has been observed in solution lineations measured in conglomerates of the Aliaga basin, the attitudes of lineations on each measuring station being strongly clustered around the mean, with standard deviations of 11.5° for azimuth and 6.3° for plunge, respectively (Simón, 2006, 2007). This constitutes an extreme deformation regime in which the principal compression and shortening axes (σ_1, e_3), as well as flow trajectories, are parallel to each other (see 2D model in Fig. 3B). This involves maximum volume reduction (the total shortening parallel to σ_1 is rendered into volume loss: $\Delta V = e_3$), which could be achieved if deformation occurs at a rate that can be accommodated by dissolution and migration of soluble material.

This deformation pattern is the opposite of that of typical elastic solids, which reflect a tendency to conserve their external volume under compressive stress, undergoing expansion along directions orthogonal to the maximum shortening axis. The same may occur for granular materials in which no mechanism of mass transfer operates; as explained above, in such cases the finite strain of the rock body can be accommodated either by rotation and translation of individual grains or by failure across them. This deformation path is recorded by divergent radial patterns of solution lineations around pebbles (Fig. 3A) (Estévez and Sanz de Galdeano, 1983; Hyppolite, 2001), which cannot occur unless matrix grains are free to move in any direction.

Rheology of the matrix is therefore a critical factor influencing the deformation pattern, the effectiveness of pressure solution for accommodating shortening, and hence the volume reduction of the rock

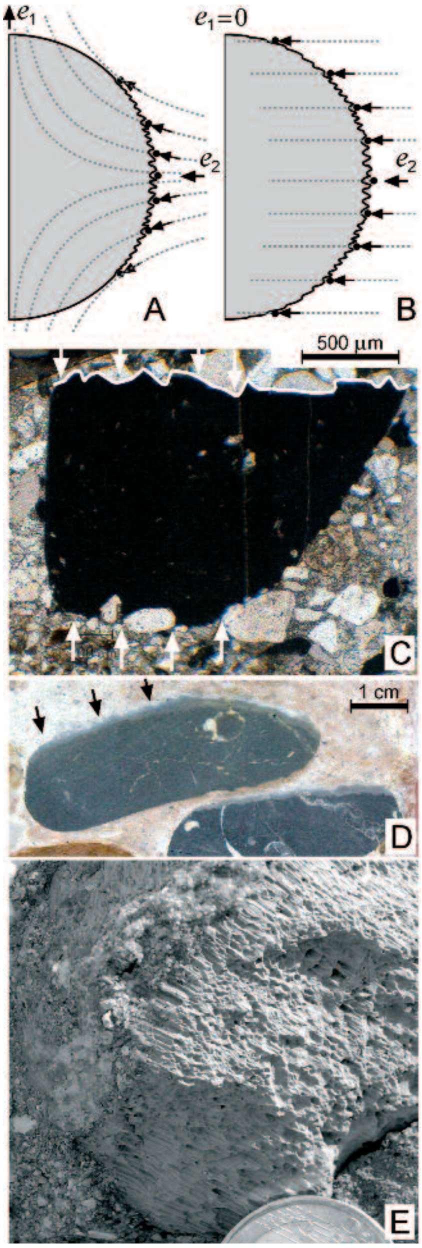

Fig. 3. A) and B) Extreme kinematical 2D models of bulk strain in conglomerates, as revealed by flow trajectories of matrix particles (dotted grey lines): A) pure shear, constant-area (DA = 0); B) net shortening, maximum area reduction ($e_1 = 0$; DA = e_2; e_1 and e_2: 2D strain axes). C), D) and E) Microscopic and mesoscopic expression of model B: stylolitic surfaces developed at the interface between two distinct flow units: pebble and matrix+cement.

Fig. 3. A) y B) Modelos cinemáticos 2D extremos de deformación en conglomerados, expresados por lineaciones de disolución que registran las trayectorias de flujo de las partículas de la matriz (líneas discontinuas grises): A) cizalla pura, área constante (DA = 0); B) acortamiento neto, máxima reducción de área ($e_1 = 0$; DA = e_2; e_1 y e_2: ejes de deformación en 2D). C), D) y E) Expresión micro- y mesoscópica del modelo B: superficies estilolíticas desarrolladas en la interfaz entre dos unidades de flujo diferenciadas: canto y matriz+cemento.

body. Rheology determines which are the flow units for each deformation mechanism. In our case, such flow units cannot be represented by individual matrix grains. On the contrary, the ensemble of pasted insoluble grains acts as a single flow unit against the pebble.

In such conditions, the interface between pebble and matrix+cement can be described as a single stylolitic joint (Fig. 3C,D,E), which explains why flow trajectories of grains are compelled to parallel each other. We easily infer that such deformation pattern requires previous cementation of the matrix, a condition that (as explained above) was accomplished in the case of conglomerates of the Aliaga basin.

As an approach, strain has been quantified in conglomerate samples belonging to units T3 and T5. 2D field sections, approximately parallel to the local $\sigma_1 // e_3$ axis (e.g., Fig. 4A,E), have been analyzed using: (i) Fry's method (Fry, 1979), which allows a broad estimation of the bulk strain based on the resulting distribution, around each pebble centre, of the neighbouring pebble centres, and (ii) numerical analysis of pressure-solution component of strain by measuring elongation in multiple directions from indented neighbouring pebbles (see example in Fig. 4). Results of both procedures are not consistent with each other, both in orientation and shape of the resulting strain ellipse. Fig. 4B,C shows the only case in which the strain axes are nearly parallel, although the strain ratio is quite different. This suggests that most of the apparent rock anisotropy shown by Fry diagrams records either a primary fabric or pre-cemention clast re-arranging. In any case, the calculated maximum shortening due to pressure solution is 8% ($1 + e_2 = 0.92$) in the sample analyzed in Fig. 4A,B,C; about 10-12% in other samples belonging to unit T5, and up to 20% in the extreme example shown in Fig. 4E (unit T3).

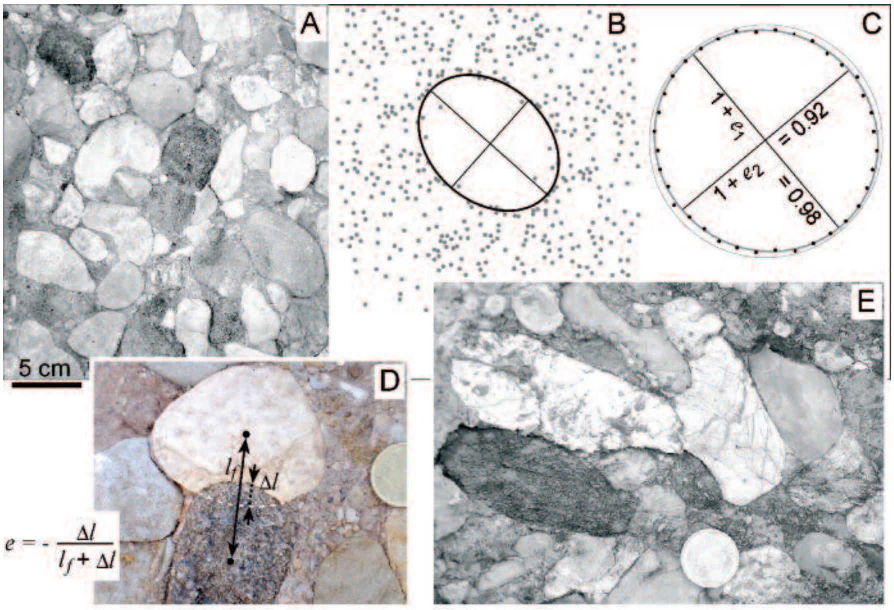

Fig. 4. A) T5 sample submitted to estimation of total strain by Fry's method (B), and to numerical analysis of pressure solution strain from indented pebbles (C, D). E) T3 sample undergoing more intense pressure solution deformation (further details in text).

Fig. 4. A) Muestra de T5 en la que se ha estimado la deformación total por el método de Fry (B), y se ha cuantificado la deformación por presión-disolución a partir de cantos indentados (C,D). E) Muestra de T3 con deformación por presión-disolución más intensa (más detalles en el texto).

Conclusions

During tectonic deformation, conglomerates of the Cenozoic Aliaga basin underwent ductile behaviour, with almost complete absence of faults and fractures. Internal deformation was mainly accommodated by pressure solution, favoured by high solubility of limestone pebbles in relation to matrix silicic grains, and, very probably, also by low strain rates. This kept the rock from stress accumulation and subsequent brittle failure.

Lithogenic history of conglomerates also played a relevant role in the deformation pattern, since it influenced their rheological behaviour. Petrography of conglomerates suggests that most of them were cemented prior to deformation. The low relative mobility between clasts prevented matrix grains from free-flowing around pebbles. Instead, the ensemble matrix-cement behaded as a rigid flow unit, its interface with a soluble pebble becoming a single stylolitic surface.

Solution lineations (orthogonal stylolites grading to oblique slickolites and parallel striations) tend to be consistently parallel to the maximum shortening and compression axis. Since no orthogonal extension operates, this deformation pattern results in maximum volume reduction (the total shortening parallel to σ_1 is rendered into volume loss: $\Delta V = e_3$), and constitutes the opposite case to that of radial, centrifugal lineations involving constant-volume deformation.

Shortening due to pressure solution in the studied conglomerates has been evaluated in the order of 8-20%, the dissolved carbonate mainly being transferred through fluid phase out of the system. This results in net mass loss and significant lithological (textural and compositional) changes.

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