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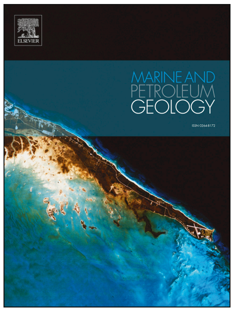

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Marine and petroleum geology

Alternative methods for calculating compaction in sedimentary basins

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Abstract

Subsidence analysis is an important technique in the study of sedimentary basins but the effects of compaction must be "backstripped". The compaction of sediments is also of importance for petroleum and water reservoir research with very important economic derivations. Most methods for calculating compaction are based on empirically derived porosity-depth relationships from a variety of known sediment types. The challenge of this paper is to apply alternative methods for calculating compaction in sedimentary basins based on: physical calculation with elastic by Steinbrenner, oedometric and change of the specific weight of the sediment methods; and use of Loadcap software. The Triassic to Lower Miocene 3025 m thick succession of Sierra Espuña (SE Spain) is used as case study for the calculations. In this succession former mineralogical studies and apatite fission-track suggested an original thickness between 4 and 6 km. The validity of each one of the proposed methods is discussed, as well as, compared for the whole succession compaction but also separately for hard vs soft sediments and for thick vs thin beds. The compaction values obtained with the alternative methods are similar to those resulting with the lower-limit curves of the porosity-depth change method. The new methods have provided values slightly higher than 4 km for the whole original thickness using the geotechnical software and the change of the sediments specific weigh methods; meanwhile values below 4 km for other methods. So, in our opinion, the geotechnical software and the change of the specific weight of the sediment methods are compatible with mineralogical constraints and also, the input data are usually better known and easier to determinate. Otherwise, the elastic method seems only accurate for soft sediments; meanwhile the oedometric method is highly influenced by the thickness of the considered beds.

Keywords: Sediments compaction calculating, physical calculation, use of geotechnics-engeenering software, basin analysis, Sierra Espuña succession.

1. Introduction

Subsidence analysis is central to the study of sedimentary basins (Allen and Allen, 1990; *and refereces therein*). Several types of stratigraphic data are needed to perform this kind of analysis, such as a detailed stratigraphic column showing present-day thicknesses, types of lithologies, ages of horizons, and estimated paleodepths (Watts and Ryan, 1975; Van Hinte, 1978; Watts, 1978; Watts, 1981).

There are three main elements to consider in the subsidence analysis procedure (Van Hinte, 1978; Mayer, 1987): sedimentary record of the basin, compaction and paleobathymetry. The present day thickness and the exact lithology of each stratigraphic unit of a basin must be collected. At effect of compaction must be removed in order to estimate the original thickness of sediments. As sedimentary units compact after deposition, the thicknesses measured today are smaller than those deposited. The changes (if those took place) in paleowater depth must also be taken into account to avoid underestimating the true amount of basin subsidence and also because that water loading can also result in compaction.

The effects of sediment compaction must be "backstripped" and most of the methods used for calculating compaction are based on empirically derived porosity-depth relationships from a variety of sediment types (Steckler and Watts, 1978; Bond *et al*., 1983; Kominz *et al*., 2011). Those methods seek to calculate the thickness of a sedimentary unit at the time of deposition according to the decrease in porosity of the sediment during burial. In these calculations it is assumed that volume of grains does not change during the burial, no significant diagenesis takes place, and porosity decreases with depth. Troubles arise with the effects of overpressured horizons, the cementation and diagenesis, and with the exact lithologies involved (Allen and Allen, 1990). Recent studies indicate that the change of porosity with depth is exponential until a certain depth, meanwhile at deeper depths the curves show uniform porosity (compaction proceeds extremely slowly) due to the decrease in hydroconductivity at higher pressures (Fowler and Yang, 1998; 1999). Two types of mechanical compaction therefore have to be considered: poroelastic at shallow depth (the most important) while viscoelastic at great depth (with less importance) (Yang, 2001; Cheauveau and Kaminski, 2008). For other authors (Stefaniuk and Mackowski, 2000) the former types take place in two phases: a syngenetic (early and of the utmost importance) and a postgenetic (later and almost negligible). A large number of compaction curves for several lithologies appear in literature with great differences among them (Marcusen, 2009) and, in some cases, for the compaction of a concrete lithology, a range of variability (with low- and upper-limits) is proposed (Bond *et al.*, 1983). Moreover, stratigraphic units usually are made of a mixture of lithologies (Kominz *et al.*, 2011). Also, the role of the mineral content of sediments seems to influence the capability of compaction of sediments (Marcusen *et al*., 2009; Bjorlykke, 2014).

Some published works explored other ways for determining compaction (Meckel *et al*., 2006; 2007; Cheauveau and Kaminski, 2008). Therefore, numerical models using elastoplastic mechanical and chemical concepts (Schneider *et al*., 1996), or geotechnical data of modern depositional environments (Meckel *et al*., 2006; 2007), have been introduced. In some cases, compaction is lower than expected (Meckel *et al*., 2006; 2007). Other numerical calculations are based on the Burger-type model to determine the implications of transient rheology for viscous compaction (Cheauveau and Kaminski, 2008), or in other cases, as in Mars, the lack of empiric studies has propelled researchers to explore other numerical calculations (Gabasova and Kite, 2018).

This is a challenge of main important because the role of compaction is not only central in determining the subsidence of sedimentary basins, but also for migration of petroleum and water reservoirs, which have very important economic derivations (Fowler and Yang, 1998; Suetnova and Vasseur, 2000; Cheauveau and Kaminski, 2008; Marcusen *et al*., 2009; Benjamin and Nwachukwu, 2011; Bjorlykke, 2014; *among others*).

Taking into account the aforementioned, this paper applies other known methods for calculating compaction in sedimentary basins. The proposed alternative methods for compaction modeling are of two types: (1) physical calculation by elastic method (Steinbrenner, 1936), oedometric, and change of the specific weight of the sediments; (2) use of geotechnical and engineering software for calculating compaction. The validity of each one of the proposed methods is discussed, as well as, compared with the results obtained using two curves of change of porosity with depth from literature.

The input values used for the calculations are measured in field, are standards derived from literature tables and/or supplied by a company of geotechnical studies - Esfera Consultores. This company has conducted laboratory tests on unconsolidated sediments from the floors of the harbors and of consolidated sediments at a certain depth of these same harbors. In any case, the same values of final thicknesses, physical properties, coefficients and modules are used in the different methods allowing a valid comparison.

The Mesozic-Cenozoic succession of Sierra Espuña (SE Spain), with a outcropping Mesozoic and Cenozoic complete marine succession (Martín-Martín *et al.*, 1997; Martín-Martín *et al.*, 2006a,b; Perri *et al*., 2017), is used as the case study for the calculations.

2. Methods

The application of alternative methods for calculating compaction tries to reproduce the conditions in sedimentary basins from the beginning of sedimentation (when soft sediments are deposited on marine or lacustrine floors) to the exhumation of the basin, while passing through the burial to depths of about 4000 m for the older beds. There are three phases of sediment evolution in sedimentary basins during burial (Allen and Allen, 1990): (1) unconsolidated sediments; (2) consolidated sediments; and much later, (3) lithified sediments (sedimentary rocks), when diagenesis processes, cementation and main compaction took place as well. Main compaction happens in early phases when sediments are soft and saturated with water (Fowler and Yang, 1998; 1999; Stefaniuk and Mackowski, 2000; Yang, 2001; Cheauveau and Kaminski, 2008). In these early phases, pores are reduced and water is expelled during the burial due to the loading of successive beds. Total compaction is the sum of the compactions in the three stages. Young and Oedometric Modules and Poison Coeficient are used in appropriate way for the aforementioned stages of sediments. These are standards derived from literature tables for lithified sediments; and supplied by a company of geotechnical studies - Esfera Consultores. This company has conducted laboratory tests on unconsolidated sediments from the floors of the harbors and of consolidated sediments at a certain depth of these same. Usually, the Young and Oedometric Modules for lithified sediments are of an order of magnitude 100 times greater than those of unconsolidated sediments. Therefore, the obtained compactions for lithified sediments are of less than 5 % than those of unconsolidated sediments, compaction in this phase being almost negligible when compared with the compaction suffered before the lithification.

This section introduces the methods from literature and other alternative methods proposed in this paper, for calculating compaction. The section is divided into the following sub-sections: (2.1) the backstripping procedure (necessary for obtaining the original thickness in a sedimentary basin analysis; (2.2) the traditional method for calculating compaction with porosity-deph change empiric curves; (2.3) methods of physical calculation applied to calculate compaction; (2.4) the elastic by Steinbrenner method; (2.5) the oedometric method; (2.6)

Change of specific weight of the sediment; (2.7) Methods based on the use of geotechnical software (the loadcap engineering software). Although most of these methods (elastic, oedometric, loadcap software) are developed for a rectangular load on a rigid base and calculated as a shortening due to compaction in the surface of the load, the compaction can be calculated for fractions of 1/3 of the width of a rectangle and 10,000 m have been estimated for that width.

2.1. The backstripping procedure

In the application of the proposed methods for calculating compaction, a backstripping procedure must be performed to obtain the original thickness of the stratigraphic levels. Backstripping uses the standard technique (Steckler and Watts, 1978; Sclater and Cristie, 1980; Allen and Allen, 1990; Roberts *et al.*, 1998; Wagreich and Schmid, 2002; Van Sickel *et al.*, 2004; *among others*) by isolating the stratigraphic units one-by-one, and then sequentially removing or backstripping in reverse order. By successive backstripping, the deepening history of the basin can be plotted in several steps, one for each “stripped off” stratigraphic units. In the case of the Sierra Espuña Succession, 18 stratigraphic levels are considered (Table 1), so 17 backstripping steps have been performed in each method.

2.2. Porosity-depth change (traditional method)

This method seeks to estimate the thickness of a sedimentary unit at the time of deposition (T_0) according to the decrease in porosity of sediment during burial. This is the traditional method used in literature in determining the compaction. In these calculations it is assumed that the volume of grains does not change during the burial and porosity decreases exponentially with depth. Several empirical curves are proposed in literature (Steckler and Watts, 1978; Sclater and Christie, 1980; Bond *et al.*, 1983; Poelchau *et al.*, 1997; Marcussen, 2009; *among others*). We have obtained the original and final porosity from the curves from Steckler and Watts (1978) and from Bond *et al.* (1983). The first one is a single smoothed exponential curve valid for all lithologies. In all cases of this curve, the original porosity of the rocks is close to 55 %, meanwhile the end porosity depends on the burial. The second (Bond *et al.*, 1983), is a set of double exponential lithology-dependent curves with a low- and upper limits of compaction of the same lithology. In addition, in the case of the lower-limit an early cementation is assumed for carbonate and siliceous rocks. In this second curve the original porosity can range from 20 to 80% depending on the original lithology, meanwhile the present porosity also depends on the depth, but according to the lithological types. In both cases, the original thickness is obtained from Equation 1 from Van Hinte (1978), where $Ø_0$ is the original porosity, T_N is the thickness measured today and $Ø_N$ the present-day porosity. $Ø_0$ and $Ø_N$ can be corrected for large thicknesses of the stratigraphic units (Bond and Kominz, 1984).

$$T_0 = T_N \frac{(1-\phi_N)}{(1-\phi_0)} \quad (1)$$

2.3. Methods based on physical calculation

Three proposed methods for physical calculation are: elastic (Steinbrenner, 1936), oedometric, and change of specific weight of the sediment. The input values used for these calculations are the final thicknesses of the stratigraphic units (measured in the field), the specific weight (initial and final), the oedometric and elastic modules and the Poisson coefficient. The physical properties are standards obtained from tables from literature and also from real data coming from engineering and geotechnical studies by the Company Esfera Consultores de Construcción. In any case, in all the methods the same values have been used allowing a valid comparison.

2.4. Elastic by Steinbrenner

This method (Steinbrenner, 1936) was derived for a rectangular load on a rigid base and calculated as the shortening due to compaction in the surface of the load (s_c) through the Equation 2 (Schleicher, 1926) and the shortening (s_z) in depth (z) of the compressed bed (with an indefinite thickness) through the Equation 3. The compaction can be calculated for fractions of 1/3 of the width of a rectangle (10,000 m have been estimated for that width). The total shortening is the difference between the two former values. The estimated initial thickness of the beds has been considered to be the depth (z) in all the cases. This value must be backstripped each time a new layer (with its respective load) is superimposed.

$$s_C = 2kqb\frac{(1-\nu^2)}{E'} \quad (2)$$

$$s_Z = \frac{qb}{2E'}(A\phi_1 - B\phi_2) \quad (3)$$

In these equations k is a shape coefficient depending on a and b, q is the increase of effective stress in the top of the compressible bed (depending of the specific weight), a is the length and b is the width in shape of the load bed, z is the initial thickness of the compressible bed, ν is the Poisson coefficient, E' is the elastic module of the compressible bed, A is equal to $1 - \nu^2$, B is $1 - \nu - 2\nu^2$, and ϕ_1 and ϕ_2 (Steinbrenner, 1936) are parameters depending on a, b and z. This method considers compressible materials in a consolidated-sediment state and does not take into account the previously suffered shortening (in an unconsolidated-sediment state). For this unconsolidated shortening, a reduction, according to literature (Feiner et al. 1976; Ministerio de Fomento, 2009) has been previously introduced to the materials: 3% for mostly granular materials, 4 % for mostly carbonated, 5% for mostly clayey. Calculation for the lithified phase has also been performed with the same procedure as for unconsolidated sediments but using appropriate elastic modules. Total compaction is obtained as the sum of the compactions in the three stages (unconsolidated sediments, consolidated sediments and lithified sediments).

2.5. Oedometric

This method (Terzaghi and Peck, 1976; Barnes, 2000; Atkinson, 2007) allows the estimation of the shortening considering oedometric conditions of load, i.e., the effective stress increase is constant throughout the compressible bed. This method has some constraints: (1) the main compaction is produced in the unconsolidated stage and due to the thickness and weigh of the bed itself; (2) each bed is homogeneous and saturated in water; (3) the permeability coefficient and the oedometric Module are constants and Darcy Law is fulfilled; (4) the compaction is mainly due to pore reduction. This method has been applied assuming an initial unconsolidated stage for the sediments of compressible beds, later, a stage of consolidated sediments, and finally a stage of lithified sediments. Total compaction obtained is the sum of the compactions in the three stages. The oedometric module for the unconsolidated stage is lithological dependent and has been obtained from literature and also from real data coming from engineering and geotechnical studies from the Company Esfera Consultores de Construcción. Otherwise, for the consolidated one, the value has been obtained from Equation 4, of common application in geotechnical studies (Jiménez Salas *et al*., 1980; Rodríguez Ortíz, et al, 1995), E_m being the oedometric module, *E'* the elastic module and *ν' the* Poisson coefficient.

$$E_m = E'\frac{1-\nu'}{1-\nu'-2\nu'^2} \tag{4}$$

In both phases the shortening is obtained through the normal equation of the oedometric method (Equation 5).

$$\Delta H = H_0 \Delta\sigma' \frac{1}{E_m} \tag{5}$$

In this case, ΔH is the shortening of the compressed bed, H_0 the initial thickness of the former, $\Delta\sigma'$ the increase of effective stress in the middle point (of the initial thickness) of the compressed bed (depending on the specific weight) and E_m its oedometric module. $\Delta\sigma'$ for initial unconsolidated stage has been determined as a fraction (2/3) of load of the bed itself; meanwhile in the consolidated stage corresponds with the load of the overlaying one. Calculation for the lithified phase has also been performed with the same procedure as for consolidated sediments only now using the appropriate oedometric modules.

2.6. Change of specific weight of the sediment

This method considers conditions without important changes in the weight of sediments. Therefore it can be calculated what are the initial conditions using the Equation 6 and the final conditions using Equation 7, γ being the specific weight, W the weight, V the volume, H the thickness and S the surface of each bed, meanwhile the subscripts $_0$ and $_f$ belong to the initial and final stages respectively.

$$\gamma_0 = \frac{W}{V_0} = \frac{W}{H_0 S} \tag{6}$$

$$\gamma_f = \frac{W}{V_f} = \frac{W}{H_f S} \tag{7}$$

Operating in both former equations to isolate *W/S* and making this relation equal in both equations, Equation 8 can be obtained, which provides the initial thickness according to the final thickness and the initial and final specific weights of each bed.

$$\gamma_0 H_0 = \gamma_f H_f \implies H_0 = H_f \frac{\gamma_f}{\gamma_0} \tag{8}$$

This method is based on similar principles to that of the porosity method, but the specific weight is a parameter which is much less variable than the porosity, and is much easier and quicker to obtain through laboratory analysis. Nevertheless, in this work these values have been obtained from the large amount of related literature (Rodríguez Ortiz *et al.*, 1995; Grundbau-Taschenbuch, 1980; NAVFAC DM 7-1 y 7-2, 1986; González de Vallejo, 2002) and also from real data coming from engineering and geotechnical studies from the Company Esfera Consultores de Construcción.

2.7. Methods based on the use of geotechnical software

The program "Loadcap" by "Geostru Software" licensed to the University of Alicante (reference nº G38RJ2), traditionally used in geotechnical studies to calculate the compaction of sediments with an embankment overload, is used in this study for calculating compaction suffered by sediments. To calculate the compaction, the program requires the thickness, the mean saturated density and the mean oedometric module (a parameter related to the stretching and the % of pores in the sediments or rocks, and by extension, to the capability of compaction) of each stratigraphic unit of the basin. The saturated density and the oedometric module are standards and are easily obtained from literature tables (Jiménez-Salas, 1975; González de Vallejo, 2002). The mean density used is saturated since sediments take place in water realm. For the stratigraphic units the mean oedometric modules were calculated in three conditions: when the unit is the last deposited (unconsolidated sediments), when a new bed is deposited and the former sediments have been compacted (consolidated sediments), and when two or more beds have been deposited and sediments have been lithified (sedimentary rocks). The mean density and the mean oedometric module were calculated according to the aforementioned stages in each case and the thickness of each bed composing the sedimentary record. The possibility of overconsolidated beds can also be considered as an input in the program.

3. Geological framework of the proposed case study succession

The Sierra Espuña area is located in the west of Murcia province in SE Spain (Fig. 1A) belonging to the Betic Cordillera from the Western Alpine Perimediterranean Orogen (Guerrera *et al*., 1993). This area (Fig. 1B) is structured as an antiformal stack (Martín-Martín and Martín-Algarra, 2002; Martín-Martín *et al*., 2006b). In the antiformal stack of Sierra Espuña six tectonic units crop out. The detachment level of the thrusts of the entire area is the Paleozoic-Triassic boundary, being the Paleozoic almost entirely removed by tectonic lamination (Martín-Martín and Martín-Algarra, 2002). The upper two units (Morrón de Totana and Perona, respectivelly) include a Triassic to Tertiary sedimentary cover. The Morrón de Totana unit shows one of the most developed, thick and well preserved Meso-Cenozoic succession of the central-western Mediterranean area (Martín-Martín *et al.*, 2006a, b; Critelli *et al.*, 2008; Critelli, 2018; Perri *et al*., 2013, 2017) and is of great interest for our purposes being almost completely composed of a Triassic to Early Miocene succession (Tables 1 to 6). The thicker sections of this succession have been selected for calculating compaction. The selected Mesozoic succession is more than 1000 meters thick and made up of Triassic and Jurassic sediments followed by a thin Cretaceous succession. The Triassic succession (Saladilla Fm: Jabaloy-Sánchez et al. 2019) comprises four levels (T1 to T4) consisting of continental redbeds with calcareous and conglomeratic intercalations belonging to shallow marine-transitional and continental realms. At the end of the Triassic succession, conformably the Jurassic succession (Castillón Fm: Jabaloy-Sánchez et al. 2019) appears. This is a shallow marine succession (J1 to J3) with three levels made of dolostones, at the base, followed by several limestone facies evolving upward to nodular limestones at the Late Jurassic. The thin Cretaceous succession (C1) shows limestones appearing in continuity over the Late Jurassic succession, sandy glauconite-rich marls and marly-limestones and marls at the top. The Mesozoic succession is followed, after an unconformity, by a thick (close to 1700 m) Tertiary succession composed of several carbonate and marly formations (E1 to E3: Mula, Valdelaparra, Espuña, Malvariche, Cánovas and As Fms; and O1-O2: El Bosque Fm: Jabaloy-Sánchez et al. 2019) evolving from shallow marine (during the Paleogene) to deep marine realms in the Early Miocene (M1A to M1C: Río Pliego and El Niño Fms: Jabaloy-Sánchez et al. 2019). It is believed that, after M1C was deposited, exhumation began in the area and no more deposits took place in the area (see below).

In the Early Oligocene, a tectonic phase took place and the tectonic Perona Unit (PU) appears thrusting on the Lowermost Oligocene Succession and is unconformably covered by the rest of the Succession (Oligocene and Early Miocene).

In this succession a mineralogical, petrographical and geochemical study was performed on the Triassic redbeds by Perri *et al.* (2013). Illite crystallinity values, illitization of kaolinite, occurrence of typical authigenic minerals and apatite fission-track studied suggested burial depths of the base of the Triassic succession of 4 to 6 km with temperatures of 140-160 ºC, typical of the burial diagenetic stage. The exhumation of the succession was also dated at 15.6 Ma (Early Langhian) when a rapid cooling below the 110 ºC isotherm took place.

--------------- Figure 1 --------------

4. Result of calculating

4.1. Porosity-depth change (traditional method)

For the calculations of the original thickness two curves have been used (Fig. 2, Table 2): from Steckler and Watts (1978) and from Bond *et al.* (1983). With the curve from Steckler and Watts (1978) the original porosity in all the cases is close to 55 % of the whole rock and the end porosity range from 8 to 54 % according to the depth (Table 1). In the case of the curves from Bond *et al.* (1983) a set of double exponential lithology-dependent curves appear with a low- and upper limits of compaction of the same lithology. If the set of lower-limit curves is taken into account (an early cementation is assumed) the original porosities range from 20 to 55 %, and the end porosities range from 2 to 29 % of the whole rock depending on the lithology and the depth (Table 1).

--------------- Figure 2 -------------

--------------- Table 1 --------------

With the curve from Steckler and Watts (1978) the whole succession (thickness of 3025 m), becomes 4863 m thick when decompaction is performed (Fig. 3). It presents a thickness reduction of 1838 m. This curve provides a high degree of compaction in deeper levels, while progressively decreasing in shallow levels. In deep levels, in most cases, the thickness becomes double if compared to the measured.

In the case of the calculations with the set of lower-limit curves from Bond *et al.* (1983) the whole succession becomes 4012 m thick (Fig. 3) after decompaction (thickness reduction of 987 m). With these lower-limit curves the sedimentary sequences made of soft sediments (silts, clays, marls, sands and gypsums) became compacted in a high degree (even more than with the curve of Steckler and Watts, 1978). This can be seen in the soft Triassic (T2) sequence with 100 m measured becoming 207 m thick after decompaction. Contrary, sequences with hard lithologies (carbonates, conglomeartes, etc) appear with less compaction since they are thought to undergo early cementation. This is the case of the hard Jurassic (J1) sequence with 125 m thickness measured in the field, and with an original thickness of only 158 m.

When the mean values are obtained with both former estimations, the whole succession becomes 4441 m thick (Fig. 3; Table 1) after decompaction. It implies a thickness reduction of 1416 m.

--------------- Figure 3 -------------

4.2. Elastic by Steinbrenner

The results (Fig. 3, Table 2) indicate that the whole succession (3025 m) becomes 3631 m (a thickness reduction of 606 m). This method does not show perceptible differences among hard and soft lithologies after compaction. So, the soft Triassic sequence (700 m) becomes 923 m thick, while the also soft Eocene sequence (275 m) becomes 416 m in origin. The hard-Jurassic sequence (325 m) shows an original thickness of 386 m. The Oligocene sequence together with the Perona Unit (1250 m) changes to 1387 m in origin. The Early Miocene is 450 m thick and it becomes only 481 m after decompaction.

--------------- Table 2 --------------

4.3. Oedometric

The results (Fig. 3, Table 3) indicate that the whole succession (3025 m) becomes 3811 m (thickness reduction of 786 m). This method does not show perceptible differences in compaction values between hard and soft lithologies. So, the soft Triassic sequence (700 m) becomes 820 m thick and the soft Eocene one (275 m) becomes 305 m in origin. The hard-Jurassic sequence (325 m) shows an original thickness of 345 m. The Early Miocene is 450 m thick and it becomes 493 m after decompaction. Nevertheless, a high compaction is observed in the thicker levels such as the Oligocene sequence together with the Perona Unit (1250 m) changing to 1822 m in origin.

--------------- Table 3 --------------

4.4. Change of specific weight of the sediment

The results (Fig. 3, Table 4) indicate that the whole succession (3025 m) becomes 4020 m (thickness reduction of 995 m). Soft lithologies are compacted more than hard sediments. The Triassic sequence (700 m) becomes 982 m thick and the Eocene one (275 m) becomes 380 m in origin. The Jurassic sequence, which is made of hard carbonates (325 m), shows an original thickness of 469 m. The Oligocene sequence, made of hard carbonates and conglomerates, together with Perona Unit, which is also made of previously consolidated carbonates, change from 1250 m measured today to 1561 m in origin, by the loading of soft sediments from the thin Early Miocene sequence. The Early Miocene is 450 m thick and it becomes only 595 m after decompaction.

--------------- Table 4 --------------

4.5. Loadcap program

The results, shown in Table 5 and Figure 3, indicate that the whole succession (3025 m) becomes 4117 m. It shows a thickness reduction of 1092 m. In a similar way to the former calculations, soft lithologies suffer greater compaction than hard sediments. So, the Triassic sequence (700 m) becomes 1125 m thick after decompaction and the Eocene one (275 m) becomes 536 m in origin. The Jurassic sequence, made of hard carbonates (325 m), shows an original thickness of about 412 m. The hard Oligocene sequence together with the Perona Unit (1250 m) change to 1488 m in origin since a minor loading due to soft sediment from the thin early Miocene sequence took place. The Early Miocene sequence was deeper and a water column of 500 m was considered in the calculations. In this case, the sequence is 450 m thick and it becomes only 513 m after decompaction.

--------------- Table 5 --------------

5. Discussion

The results obtained from all the above calculations (Fig. 4) indicate that the higher compaction (37.8 %) is obtained with the porosity-depth change methods from Steckler and Watts (1978). Nevertheless, the most restrictive porosity-depth change method from Bond *et al.* (1983) using the lower-limit curves implies a compaction of 24.6 % for the studied succession (Fig. 4, Table 6). The mean value for the porosity-depth change methods provides a compaction of 31.2 % (Fig. 4). The alternative methods used for calculating compaction in the same succession (Fig. 4, Table 6), have provided a compaction rank from 16.7 % using the elastic method by Steinbrenner to 26.5 % using the Loadcap program, with intermediate values of 20.6 % using the oedometric method and 24.7 % using the specific weight method. When the mean of all methods is calculated a compaction of about 25 % is obtained. The value of 24.6 % obtained with the porosity-depth change method from Bond *et al.* (1983) using the lower-limit curves is within the average of the values obtained with the alternative methods. The standard deviation of the initial thicknesses is 195 m, while the variation coefficient is 5 %.

--------------- Figure 4 --------------

--------------- Table 6 --------------

5.1. Implications according to sediment lithology

When the results of compaction are taken into account separately for hard versus soft rocks, and for thick versus thin beds, some interesting assessments can be extracted (Fig. 4, Table 6). In the case of hard rocks, such as the carbonate Jurassic part of the succession, the highest value for compaction (44.5 %) is obtained with the porosity-depth change method by Steckler and Watts (1978). A compaction of 20.7 % is obtained with the variety from Bond *et al.* (1983) with the lower-limit curves. This value is comparable with the intermediate values obtained through the alternative methods. When the alternative methods proposed in this paper are compared, the specific weight method (30.7 %) provides higher values for the compaction of hard rocks. In contrast, the oedometric method (5.9 %) gives lower value; meanwhile intermediate values are obtained with the elastic by Steinbrenner (15.9 %) and Loadcap software (21.1 %) methods. If soft sediments, such as the Eocene part of the succession, are considered, the upper value (48.7 %) is obtained with the alternative Loadcap software method. The values for the compaction obtained with the porosity-depth change methods are: 41.4 % with the method from Steckler and Watts (1978) and 37.4 % with the method from Bond *et al.* (1983) with the lower-limit curves. In the case of the other alternative methods proposed in this paper, the Loadcap software value (48.7 %) is followed, from upper to lower, by the elastic method by Steinbrenner (33.9 %), specific weight method (27.6 %) and the oedometric method (9.8 %).

5.2. Implications according to the thickness of the beds

When a thick sequence, such as the Lower Oligocene part of the succession, is analyzed, high values for compaction are obtained with the oedometric method (40.4 %). In the case of the porosity-depth change method 14.0 % is obtained with the lower-limit curves from the Bond *et al.*, (1983) method, and 35.7 % with the method from Steckler and Watts (1978). When the alternative methods are compared from greatest to least, the oedometric method (40.4 %) is followed by the specific weight method (23.5 %), Loadcap software (18 %) and elastic by Steinbrenner (9.4 %). In the case of a thin sequence, such as the Cretaceous part of the succession, higher values for compaction are obtained again with the porosity-depth change method (49 % with lower-limit curves from the method from Bond *et al.*, 1983; 43.2 % with the method from Steckler and Watts, 1978). When the alternative methods proposed in this paper are compared, the Loadcap software (41.9 %) method provides higher values for the compaction. Otherwise, the oedometric method (3.8 %) gives lower value; meanwhile intermediate values are obtained with the elastic by Steinbrenner (32.2 %) and the Specific Weight (25.1 %) methods.

In general, similar values for compaction (but with a certain variability) are obtained using the alternative methods (Fig. 4) and in the same range of values obtained with the lower-limit curves from the method from Bond *et al.*, (1983). Nevertheless, some further constraints could be introduced due to the results of mineralogical studies performed by Perri *et al.* (2013) in the same stratigraphic succession of the study area. These studies, composing illite crystallinity values, illitization of kaolinite, occurrence of typical authigenic minerals and apatite fission-track, indicated a burial depth of the base of the Triassic succession of 4 to 6 km deep, with temperatures of 140-160 ºC (typical of the burial diagenetic stage). Taking this into account, the most plausible alternative methods could be the Loadcap program calculations (4117 m of original thickness), and the specific weight (4020 m of original thickness). Both methods are close to the value obtained with the lower-limit curves from the method from Bond *et al.*, (1983). So, these three methods appear inside but close to the lower limit proposed by Perri *et al.* (2013) of the 4000 m of depth. Moreover, the specific weight change method provides the initial thickness with the inputs of the final thickness and the initial and final specific weights of each stratigraphic level, being a method based in similar principles to that of the porosity method, but with the input of the specific weight, which is a parameter much less variable to the porosity, and much easier and quicker to obtain.

Otherwise, the compaction results obtained using the oedometric method and elastic method by Steinbrenner were below the minimum compaction required by mineralogical data from Perri *et al.* (2013). The elastic method by Steimbrenner provided the lowermost value for compaction of the whole succession (Fig. 4). This method provides very low values for compaction of hard rocks (Jurassic, Lower Oligocene and Perona Unit). In the case of these hard rocks, it is evident that cementation and diagenesis took place. On the contrary, this method seems to be much more adapted to soft clay and marl dominant sediments (Fig. 4). The constraints of the elastic method imply that compaction mainly accounts for the consolidated sediments. The possible compaction for unconsolidated sediments is assumed as negligible by this method.

On the other hand, the oedometric method provides the lowermost values of compaction for both hard and soft rocks. It also seems to be greatly influenced by the thickness of the considered beds, presenting higher compaction in thicker beds and lower in thin ones (Fig. 4). This is due to the intrinsic constraints of the method: (1) the main compaction in the unconsolidated stage; (2) the compaction is due to the thickness and weigh of the bed itself. The intrinsic constraints of the main compaction in the unconsolidated stage is in accordance to that proposed by Fowler and Yang (1998, 1999), Yang (2001), Cheauveau and Kaminski (2008) and Stefaniuk and Mackowski (2000), but regardless of that, it does not seem that compaction could only be due to the intrinsic weigh of the bed since overlaying beds should be also responsible for part of the compaction.

5.3. Implications when intra thrust systems take place

An important feature of the studied stratigraphic succession is the presence of a thrusting nappe (Perona Unit) intercalated in the succession at the Oligocene level. This can be a frequent situation in old sedimentary basins that usually are not taken into account in compaction studies. In fossil sedimentary basin is frequent this situation and also other tectonic perturbations as folds and faults. The influence of folding and faulting can easily be eliminated by restoring and balancing, so that, not affecting for compaction calculations. Nevertheless, a thrusting is a very influential element in compaction since induces an overload on the underlying succession (also could undergo its own compaction). When the compaction results from different methods are compared for this thrusting unit (Fig. 4, Table 6), high values are obtained with the porosity-depth change methods (15 % with the lower-limit curves by Bond *et al.*, 1983; 39.1 % with the method by Steckler and Watts, 1978). Those results are probably due to the fact that porosity-depth change methods do not take into account that the sediments of a tectonic unit have already been compacted due to the overlaying succession prior to the structuring in Oligocene times. In the case of comparing the alternative methods proposed in this paper, the lower (no or minimal) compaction are obtained with the specific weight (0.0 %) and Loadcap software methods (2.9 %) because these methods consider that sediments were already compacted prior to the emplacement of the tectonic unit. Intermediate (but low) similar values are obtained with the oedometric (6.9 %) and elastic by Steimbrenner (7.4 %) methods considering a low compaction due to the load of the overlaying Miocene part of the succession. The specific weight and Loadcap software methods seem to be more accurate for the compaction of the thusting unit since null or very low values for compaction are obtained, because those sediments were already compacted prior to the structuring.

6. Conclusions

- Alternative methods based on physical calculation (elastic by Steinbrenner, oedometric and change of the specific weight of the sediment) and geotechnical and engineering software (Loadcap software) are introduced to calculate compaction in the Meso-Cenozoic marine succession cropping out in the Sierra Espuña area (SE Spain).
- The inputs used for calculations (physical properties, coefficients and modules) are standards derived from literature, real data coming from engineering-geotechnical studies, and thicknesses measured in the field; but in all methods those inputs are the same allowing a valid comparison (Fig. 5).

--------------- Figure 5 --------------

- The evidence presented in this paper, indicate that compaction resulting from the application of alternative methods in old sedimentary basins are comparable with that obtained with the lower-limit curves of the traditional porosity-depth change methods (Fig. 5).
- The constraints of mineralogical studies in the same studied area (Perri *et al.*, 2013) suggest that compaction obtained with the specific weight method and the Loadcap program could be the more accurate of that alternative new methods (Fig. 5).
- Moreover, in the case of the specific weight method, it seems that it is the least affected method by the lithological type, being as valid for hard (cemented) as for soft rocks (Fig. 5).
- The elastic (Steimbrenner) method provided excessively low values for compaction of hard rocks because it considers that compaction only occurs in the consolidated stage and disregards

the latest possible compaction in unconsolidated one. Apart from that, it seems to be much more applicable to soft rocks (Fig. 5).

- The oedometric method seems to be a method greatly influenced by the thickness of the considered beds providing higher compactions in thicker beds and lower in thin ones (Fig. 5). This is due to the inherent constraints of the method regarding the assumption that compaction is due to the thickness and weigh of the bed itself in the unconsolidated stage, while disregarding the possible compaction due to overlaying beds in the consolidated stage.

- The particularity of the occurrence of a thrusting unit in the succession (very common in old sedimentary basins) is also studied. The effect of the loading in the underlying succession and the compaction of this unit have also been studied indicating that the specific weight and Loadcap software methods are the most appropriate (Fig. 5), because these methods consider that the sediments of this thrusting unit were mainly compacted prior to the tectonic emplacement.

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Figure caption

Figure 1.- A) location of the key-case study area in Sierra Espuña, Murcia province (SE, Spain); B) geological map and section of the Sierra Espuña area.

Figure 2.- Graphics with the calculations of the porosity-depth change of sediment according to Steckler and Watts (1978) and to Bond *et al.* (1983). In the case of Bond *et al.* (1983) only the set of lower-limit curves have been used for calculating compaction.

Figure 3.- Accumulate thickness-age (My) graphic with the comparative of the measured thickness and the results of original accumulate thickness along time of the studied

succession after decompaction with the whole methods. The mean thickness with the whole methods is also represented with dash line. Key: ESM: elastic by Steinbrenner; SWM: specific weight of the sediment methods; OM: oedometric method; PCM: porosity change method (Bond et al., 1983); LSM: use of Loadcap software method.

Figure 4.- Histograms with the % of compaction of the whole succession, Jurassic hard rocks, Eocene soft rocks, thicker Lower Oligocene, thinner Cretaceous and the thrusting Perona Unit.

Figure 5.- Comparative of the compaction (%) according all the methods for the whole succession; for the hardest, the softer, the thicker and the thinner intervals; and for the thrusting unit.

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Table caption

Table 1.- Results of the compaction calculating with the porosity-depth change method.

Table 2.- Results of the compaction calculating with the elastic by Steinbrenner method.

Table 3.- Results of the compaction calculating with the oedometric method.

Table 4.- Results of the compaction calculating with the specific weight change method.

Table 5.- Results of the compaction calculating with the Loadcap software method.

Table 6.- Synthesis of the results of the compaction calculating with the whole methods.

Stratigraphic Unit	Lithology (age)	Thickness	Accumulated	Original Porosity	Final Porosity	Original	Original Porosity	Final Porosity	Original	Mean value
				thick Steckler & Watts (1978)			thick Bond et al. (1983)			
Río Pliego and El Niño Fms (450 m)	M1C.- marls and siliceous marls (Burdigalian)	100 m	100	55%	54%	**102**	30%	29%	**101**	**102**
	M1B.- conglomerates (Late Aquitanian)	200 m	300	55%	50%	**222**	25%	22%	**208**	**215**
	M1A.- marls and sandstones (Early Aquitanian)	150 m	450	55%	47%	**177**	55%	27%	**243**	**210**
El Bosque Fm (950 m)	O2.- marls (Late Oligocene)	200 m	650	55%	42%	**258**	55%	25%	**333**	**296**
	O1.- conglomerados y carbonatos (Early Oligocene)	750 m	1400	55%	31%	**1167**	20%	7%	**872**	**1020**
Perona Thrusting Unit	PU.- dolostones and limestones (Liassic)	300 m	1700	55%	26%	**493**	20%	6%	**353**	**423**
Espuña, Valdelaparra, Malvariche, Cánovas and As Fms (275 m)	E3.- marls (Late Lutetian-Earliest Oligocene)	100 m	1800	55%	23%	**164**	55%	13%	**193**	**179**
	E2.- clays (Early Lutetian)	50 m	1850	55%	22%	**86**	55%	12%	**98**	**92**
	E1.- Calcarenites (Ypresian	125 m	1975	55%	21%	**219**	20%	5%	**148**	**184**
Cretaceous (25 m)	C1.- limestones, marly limestone and sands (Cretaceous)	25 m	2000	55%	21%	**44**	55%	11%	**49**	**47**
Castillón Fm (350 m)	J3.- nodular limestones (Malm)	75 m	2075	55%	20%	**133**	25%	6%	**94**	**114,0**
	J2.- Limestones and marlylimestones (Dogger)	125 m	2200	55%	19%	**225**	25%	5%	**158**	**192**
	J1.- Dolostones (Liassic)	125 m	2325	55%	18%	**228**	25%	5%	**158**	**193**
Saladilla Fm (700 m)	T4.- clays with gipsum (Norian-Raethian)	25 m	2350	55%	14%	**48**	55%	9%	**51**	**49**
	T3.- limestones (Carnian)	375 m	2725	55%	12%	**733**	25%	3%	**485**	**609**
	T2.- clays, sands and sandstones (Ladinian)	100 m	2825	55%	10%	**200**	55%	7%	**207**	**203**
	T1.- conclomerates and sands (Sciityan)	200 m	3025	55%	8%	**364**	25%	2%	**261**	**313**
				Total original thickness		**4863**			**4012**	**4441**
				Total thickness reduction		**1838**			**987**	**1416**

Table 1

Thickness	Accumulated	Unconsolidated sediments compaction (UC)		Consolidated sediments compaction (CC)				Lithified sediments compaction (LC)				Original thickness (To)
		To fraction (%)	Compaction (m)	σ (kp/cm^2)	E (kp/cm^2)	ν	Compaction (m)	σ (kp/cm^2)	E (kp/cm^2)	ν	Compaction (m)	
		Feiner et al. (1976)				**Steinbrenner, 1936**				**Steinbrenner, 1936**		
100	100	5,000	5,5	50,0	1000	0,10	4,9	50,0	38700	0,10	0,1	110,5
200	300	3,000	6,3	24,3	1400	0,25	2,4	24,3	44700	0,23	0,1	208,8
150	450	4,000	6,5	74,3	1670	0,18	5,4	74,3	38700	0,17	0,2	162,1
200	650	5,000	11,7	110,3	1000	0,10	23,1	110,3	31600	0,10	0,7	235,5
750	1400	4,000	33,0	158,3	2120	0,24	42,9	158,3	55200	0,22	1,6	827,5
300	1700	0,000	0,0	348,1	3300	0,23	23,3	348,1	92200	0,21	0,8	324,1
100	1800	5,000	8,8	429,1	1000	0,10	66,8	429,1	38700	0,10	1,0	176,6
50	1850	5,000	4,4	453,1	750	0,25	33,6	453,1	22500	0,23	0,7	88,7
125	1975	3,000	4,5	464,1	1800	0,30	20,7	464,1	50000	0,27	0,7	150,9
25	2000	4,000	1,5	495,3	1310	0,19	10,2	495,3	49560	0,17	0,2	36,9
75	2075	5,000	4,4	501,5	3200	0,26	8,3	501,5	86600	0,23	0,3	88,0
125	2200	5,000	7,4	521,3	3300	0,23	15,6	521,3	89500	0,21	0,5	148,5
125	2325	5,000	7,5	554,4	3300	0,23	16,7	554,4	77500	0,21	0,7	149,9
25	2350	5,000	2,4	588,1	900	0,24	19,9	588,1	25740	0,22	0,4	47,7
375	2725	5,000	22,8	593,7	3200	0,23	57,8	593,7	67000	0,22	2,5	458,1
100	2825	4,000	5,5	693,1	1800	0,27	31,0	693,1	43415	0,25	1,1	137,6
200	3025	3,000	8,3	717,9	1600	0,29	69,6	717,9	45760	0,27	1,9	279,8
		Unconsolidated Total Compaction (UC):	**140,5**			**Consolidated Total Compaction (CC):**	**452,2**			**Lithified Total Compaction (CC):**	**13,6**	
							Total thickness reduction:	**606,3**			**Original thickness:**	**3631,3**

Table 2

Thickness	Accumulated	Unconsolidated Sediments Compaction (UC)			Consolidated Sediments Compaction (CC)			Lithified Sediments Compaction (LC)			Original thickness (To)
		σ_1 (kp/cm^2)	Om (kp/cm^2)	Compactación (m)	σ_2 (kp/cm^2)	Om (kp/cm^2)	Compactación (m)	σ_3 (kp/cm^2)	Om (kp/cm^2)	Compactación (m)	
		Terzaghi, K., Peck, R., 1976			Terzaghi, K., Peck, R., 1976			Terzaghi, K., Peck, R., 1976			
100	100	12,6	228	5,8	16,8	1011	1,7	12,4	39135	0,0	107,5
200	300	28,0	537	11,0	50,1	1527	6,8	49,3	47997	0,2	218,0
150	450	19,1	277	11,1	68,4	1739	6,1	92,4	40096	0,3	167,5
200	650	26,4	228	26,2	63,3	1011	13,4	135,6	31955	0,9	240,5
750	1400	154,8	411	453,4	150,5	2298	52,6	255,3	58933	3,3	1259,3
300	1700	54,0	> 10^6	0,0	233,1	3543	21,1	390,4	97651	1,2	322,3
100	1800	12,3	228	5,7	94,5	1011	10,3	443,1	39135	1,1	117,1
50	1850	5,7	144	2,1	30,7	818	1,9	461,4	24160	1,0	55,0
125	1975	13,1	308	5,5	24,7	2066	1,5	479,9	55547	1,1	133,1
25	2000	3,1	253	0,3	28,1	1370	0,5	495,3	51396	0,2	26,0
75	2075	9,6	299	2,5	16,0	3522	0,3	508,3	92988	0,4	78,3
125	2200	16,2	344	6,2	36,6	3543	1,3	534,8	94792	0,7	133,2
125	2325	16,2	344	6,2	50,2	3543	1,8	568,3	82082	0,9	133,9
25	2350	2,7	140	0,5	36,8	974	1,0	588,1	27481	0,5	27,0
375	2725	55,1	344	71,4	56,4	3436	6,3	641,1	71432	3,4	456,1
100	2825	11,4	264	4,5	112,4	2000	6,0	702,8	47165	1,5	112,0
200	3025	26,7	355	16,2	49,0	1815	5,5	739,0	50936	2,9	224,6
			Total Unconsolidated Compaction (UC):	**628,6**		**Total Consolidated Compaction (CC):**	**138,0**		**Total Lithified Compaction (LC):**	**19,7**	
			Total thickness reduction:	**786,4**						**Original thickness:**	**3811,4**

Table 3

Stratigraphic Unit	Lithology (age)	Thickness	Accumulated	Specific Weight (T/m^3) Unconsolidated	Specific Weight (T/m^3) Consolidated	Original thickness (To)
				Grundbau-Taschenbuch, 1980; NAVFAC DM 7-1 y 7-2, 1986 and others		$H_0 = H_f \frac{\gamma_f}{\gamma_0}$
Río Pliego and El Niño Fms (450 m)	M1C.- marls and siliceous marls (Burdigalian)	100 m	100	1,78	2,48	139,3
	M1B.- conglomerates (Late Aquitanian)	200 m	300	1,99	2,45	246,2
	M1A.- marls and sandstones (Early Aquitanian)	150 m	450	1,78	2,48	209,0
El Bosque Fm (950 m)	O2.- marls (Late Oligocene)	200 m	650	1,75	2,45	280,0
	O1.- conglomerados y carbonatos (Early Oligocene)	750 m	1400	1,93	2,53	981,1
Perona Thrusting Unit	PU.- dolostones and limestones (Liassic)	300 m	1700	2,70	2,70	300,0
Espuña, Valdelaparra, Malvariche, Cánovas and As Fms (275 m)	E3.- marls (Late Lutetian-Earliest Oligocene)	100 m	1800	1,75	2,45	140,0
	E2.- clays (Early Lutetian)	50 m	1850	1,64	2,40	73,2
	E1.- Calcarenites (Ypresian	125 m	1975	1,50	2,00	166,7
Cretaceous (25 m)	C1.- limestones, marly limestone and sands (Cretaceous)	25 m	2000	1,81	2,42	33,4
Castillón Fm (350 m)	J3.- nodular limestones (Malm)	75 m	2075	1,85	2,65	107,4
	J2.- Limestones and marlylimestones (Dogger)	125 m	2200	1,85	2,65	179,1
	J1.- Dolostones (Liassic)	125 m	2325	1,85	2,70	182,4
Saladilla Fm (700 m)	T4.- clays with gipsum (Norian-Raethian)	25 m	2350	1,59	2,36	37,1
	T3.- limestones (Carnian)	375 m	2725	1,85	2,65	537,2
	T2.- clays, sands and sandstones (Ladinian)	100 m	2825	1,63	2,46	150,9
	T1.- conclomerates and sands (Sciityan)	200 m	3025	1,85	2,37	256,8
					Original thickness:	**4019,8**
					Final thickness:	**3025,0**
					Total thickness reduction:	**994,8**

*Original thickness (**T_o**), final thickness (Hf), unconsolidated specific weight (γ_o) and consolidated specific weight (γ_f)*

Table 4

Stratigraphic Unit	Levels	Measured Thickness	Corrected thickness	Back-strip. 1	Back-strip. 2	Back-strip. 3	Back-strip. 4	Back-strip. 5	Back-strip. 6	Back-strip. 7	Back-strip. 8	Back-strip. 8	Back-strip. 10	Back-strip. 11	Back-strip. 12	Back-strip. 13	Back-strip. 14	Back-strip. 15	Back-strip. 16	Back-strip. 17
Río Pliego and El Niño Fms	18.- Mioc 1C	100	115	115																
	17.- Mioc 1B	200	223	207	223															
	16.- Mioc 1A	150	175	155	157	175														
El Bosque Fm	15.- Oligoc 2	200	263	210	215	224	263													
	14.- Oligoc 1	750	912	767	774	788	800	912												
Perona Unit	13.- Perona U.	300	308	300	300	300	300	300	308											
Espuña, Valdelaparra, Malvariche, Cánovas and As Fms	12.- Eocene 3	100	230	105	107	111	115	121	146	230										
	11.- Eocene 2	50	129	53	54	57	59	63	80	89	129									
	10.- Eocene 1	125	172	128	129	132	134	137	149	155	158	172								
Cretaceous	9.- Cretac	25	43	26	26	27	28	29	33	35	36	37	43							
Castillón Fm	8.- Jurassic 3	75	91	76	76	77	78	79	83	85	86	87	88	91						
	7.- Jurassic 2	125	155	127	128	129	130	132	139	142	144	145	146	147	155					
	6.- Jurassic 1	125	163	127	128	129	130	132	139	142	144	145	146	147	148	163				
Saladilla Fm	5.- Triassic 4	25	65	26	27	28	29	31	38	42	44	45	47	47	48	50	65			
	4.- Triassic 3	375	471	381	383	388	392	398	419	429	435	438	442	444	446	450	454	471		
	3.- Triassic 2	100	225	103	104	106	108	111	121	126	129	131	133	135	136	138	140	141	225	
	2.- Triassic 1	200	351	206	208	213	217	223	246	258	264	268	273	276	279	284	289	291	308	351

	Total thickness	**3025**	**4091**	**Total thickness reduction = 1066 m**

Table 5

Stratigraphic Unit		Age (My)	Final thickness	Accumulated final thickness	Initial thickness (ESM)	Accumulated initial thickness (ESM)	Initial thickness (SWM)	Accumulated initial thickness (SWM)	Initial thickness (OM)	Accumulated initial thickness (OM)	Initial thickness (PCM)	Accumulated initial thickness (PCM)	Initial thickness (LSM)	Accumulated initial thickness (LSM)	Mean value	Accumulated mean value	Stan devi from thick (
Saladilla Fm (700 m)	Triassic-1	240	200	200	279,8	279,8	256,8	256,8	224,6	224,6	261,0	261,0	356,0	356,0	275,6	275,6	49
	Triassic-2	230	100	300	137,6	417,4	150,9	407,7	112,0	336,6	207,0	468,0	228,0	584,0	167,1	442,7	48
	Triassic-3	217	375	675	458,1	875,5	537,2	944,9	456,1	792,7	485,0	953,0	475,0	1059,0	482,3	925,0	32
	Triassic-4	204	25	700	47,7	923,2	37,1	982,0	27,0	819,7	51,0	1004,0	66,0	1125,0	45,8	970,8	14
Castillón Fm (350 m)	Jurassic-1	195	125	825	149,9	1073,1	182,4	1164,4	133,9	953,6	158,0	1162,0	164,0	1289,0	157,6	1128,4	17
	Jurassic-2	168	125	950	148,5	1221,6	179,1	1343,5	133,2	1086,8	158,0	1320,0	156,0	1445,0	155,0	1283,4	16
	Jurassic-3	150	75	1025	88,0	1309,6	107,4	1450,9	78,3	1165,1	94,0	1414,0	92,0	1537,0	91,9	1375,3	16
Cretaceous (25 m)	Cretaceous	105	25	1050	36,9	1346,5	33,4	1484,3	26,0	1191,1	49,0	1463,0	43,0	1580,0	37,7	1413,0	8
España, Valdelaparra, Malvariche, Cánovas and As Fms (275 m)	Eocene-1	65	125	1175	150,9	1497,4	166,7	1651,0	133,1	1324,2	148,0	1611,0	173,0	1753,0	154,3	1567,3	1
	Eocene-2	50	50	1225	88,7	1586,1	73,2	1724,2	55,0	1379,2	98,0	1709,0	131,0	1884,0	89,2	1656,5	28
	Eocene-3	40	100	1325	176,6	1762,7	140,0	1864,2	117,1	1496,3	193,0	1902,0	232,0	2116,0	171,7	1828,2	4
Perona Thrusting Unit	Perona Unit	35	300	1625	324,1	2086,8	300,0	2164,2	322,3	1818,6	353,0	2255,0	309,0	2425,0	321,7	2149,9	26
El Bosque Fm (950 m)	Oligocene-1	30	750	2375	827,5	2914,3	981,1	3145,3	1259,3	3077,9	872,0	3127,0	915,0	3340,0	971,0	3120,9	17
	Oligocene.2	25	200	2575	235,5	3149,8	280,0	3425,3	240,5	3318,4	333,0	3460,0	264,0	3604,0	270,6	3391,5	39
Río Pliego and El Niño Fms (450 m)	Miocene-1A	23	150	2725	162,1	3311,9	209,0	3634,3	167,5	3485,9	243,0	3703,0	175,0	3779,0	191,3	3582,8	34
	Miocene-1B	20	200	2925	208,8	3520,7	246,2	3880,5	218,0	3703,9	208,0	3911,0	223,0	4002,0	220,8	3803,6	1
	Miocene-1C	16	100	**3025,0**	110,5	**3631,2**	139,3	**4019,8**	107,5	**3811,4**	101,0	**4012,0**	115,0	**4117,0**	114,7	**3918,3**	14

ESM = Elastic Steinbrenner Method *PCM = Porosity Change Method (Bond et al., 1983)* *SWM = Specific Weight Method* *LSM = Loadcap Softhware Method* *OM = Oedometric Method*

Standard deviation of the initial thicknesses
Variation coefficient of the maximum accumulated values

Table 6

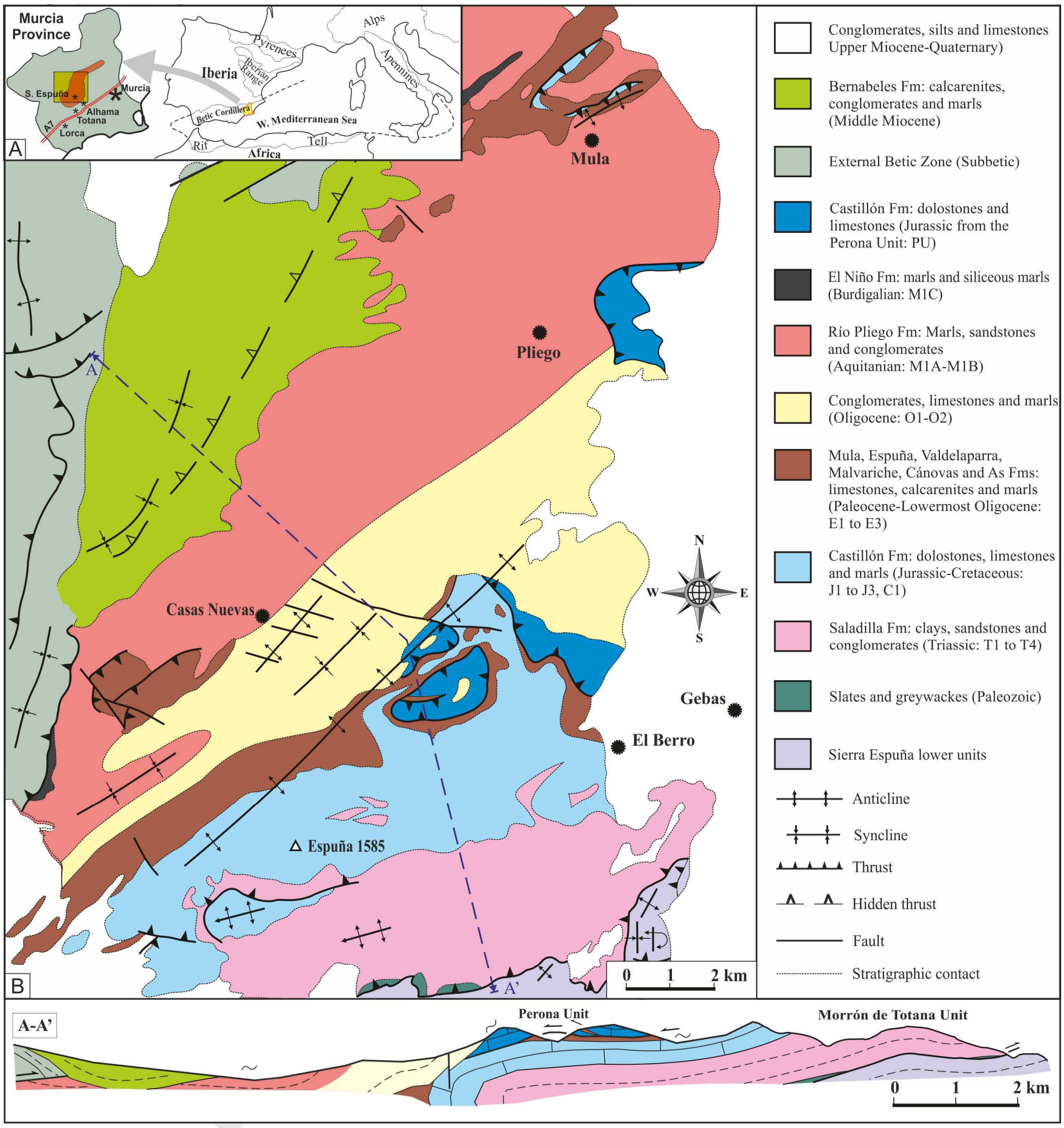
Murcia Province
S. Espuña
Murcia
Alhama
Totana
Lorca
A7
Iberia
Pyrenees
Iberian Range
Alps
Apennines
Betic Cordillera
W. Mediterranean Sea
Rif
Tell
Africa
A
Mula
Pliego
Casas Nuevas
Gebas
El Berro
Espuña 1585
N
W
E
S
0 1 2 km
B
A
A'
Conglomerates, silts and limestones Upper Miocene-Quaternary)
Bernabeles Fm: calcarenites, conglomerates and marls (Middle Miocene)
External Betic Zone (Subbetic)
Castillón Fm: dolostones and limestones (Jurassic from the Perona Unit: PU)
El Niño Fm: marls and siliceous marls (Burdigalian: M1C)
Río Pliego Fm: Marls, sandstones and conglomerates (Aquitanian: M1A-M1B)
Conglomerates, limestones and marls (Oligocene: O1-O2)
Mula, Espuña, Valdelaparra, Malvariche, Cánovas and As Fms: limestones, calcarenites and marls (Paleocene-Lowermost Oligocene: E1 to E3)
Castillón Fm: dolostones, limestones and marls (Jurassic-Cretaceous: J1 to J3, C1)
Saladilla Fm: clays, sandstones and conglomerates (Triassic: T1 to T4)
Slates and greywackes (Paleozoic)
Sierra Espuña lower units
Anticline
Syncline
Thrust
Hidden thrust
Fault
Stratigraphic contact
A-A'
Perona Unit
Morrón de Totana Unit
0 1 2 km

Figure 1

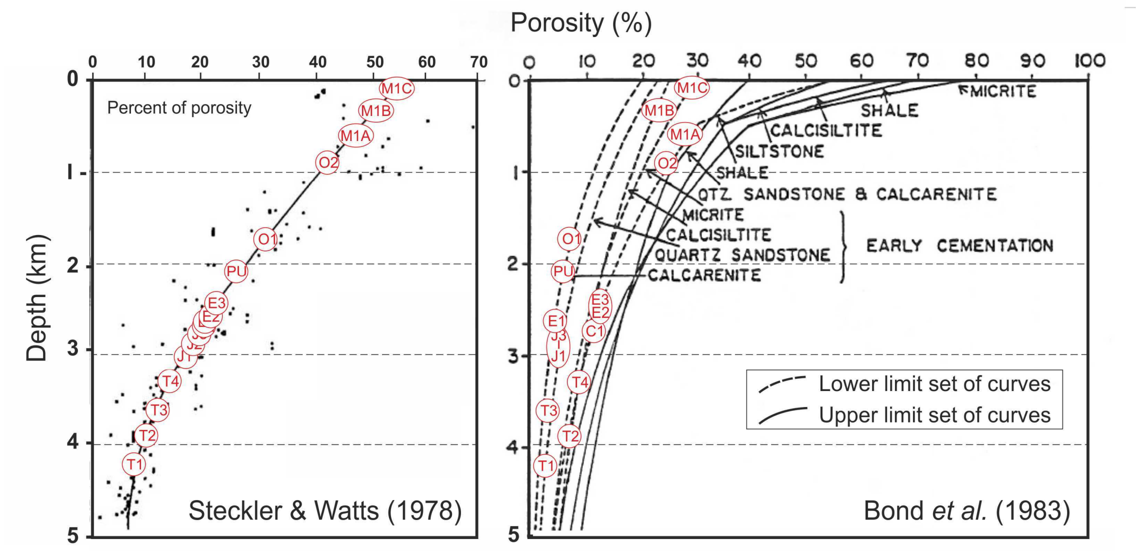

Figure 2

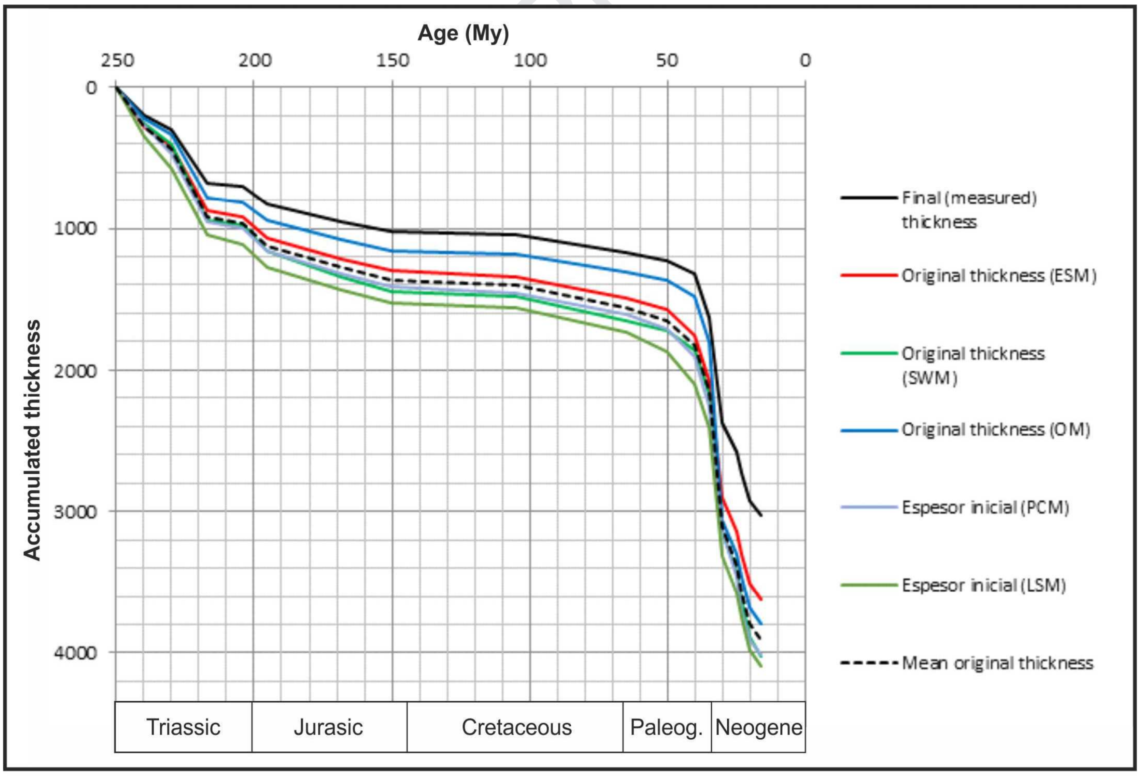

Figure 3

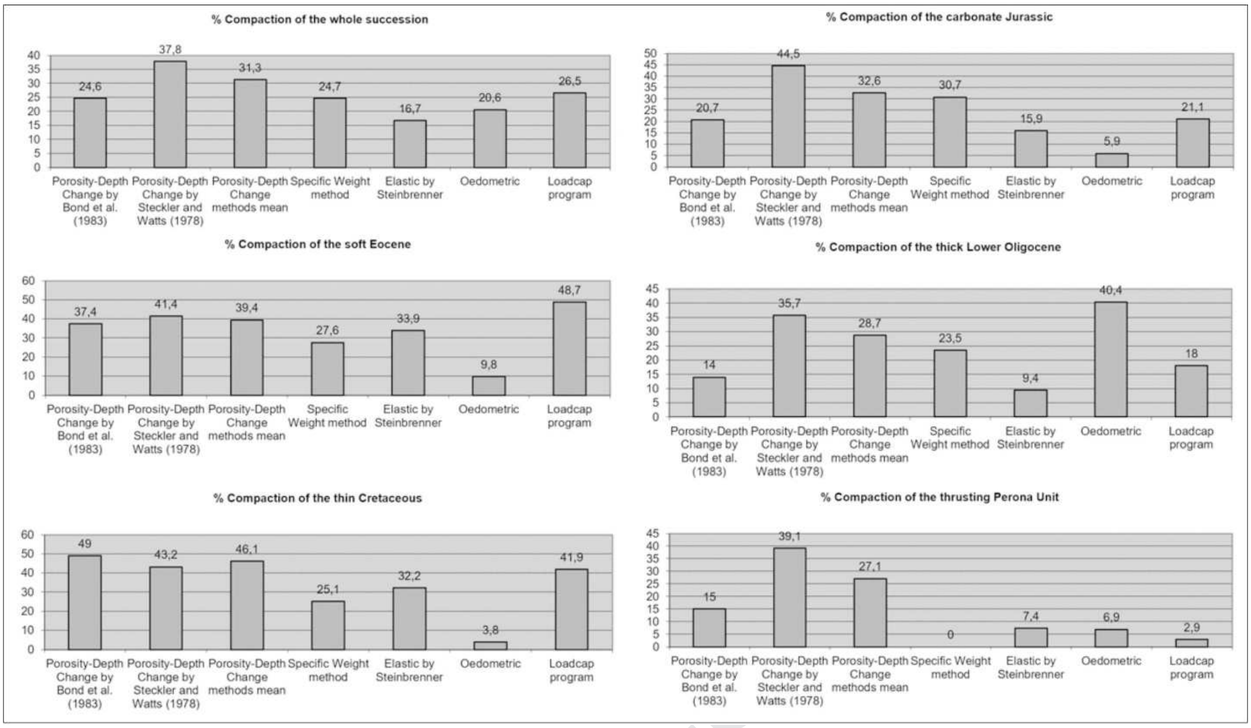

Figure 4

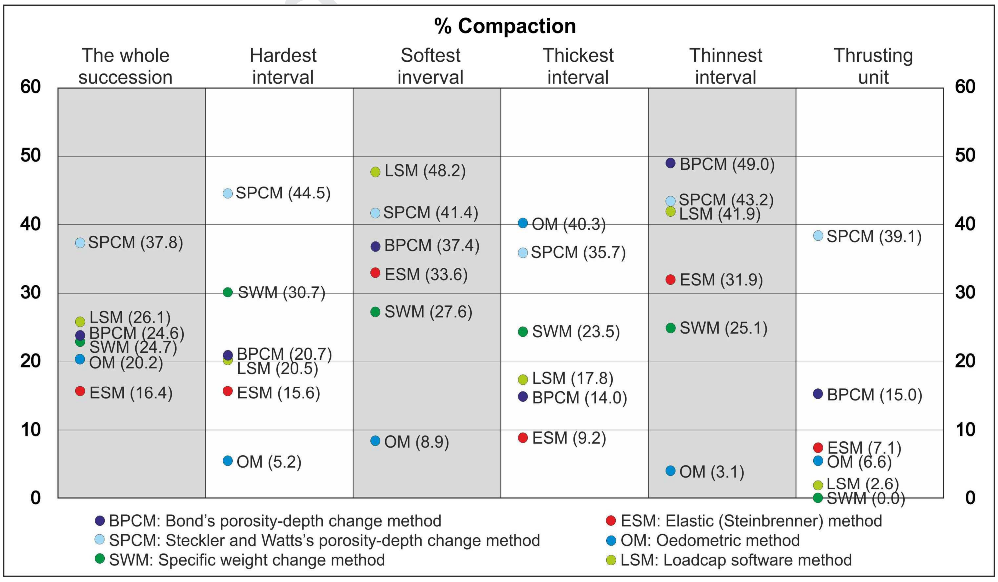

Figure 5

Alternative methods are introduced to calculate compaction.

Inputs for calculations are standards and also coming from engineering studies

Compactions resulting are comparable with porosity-depth lower-limit curves

Mineralogical constraints suggest more accurate specific weight and Loadcap program

Steimbrenner and oedometric show problems with hard rocks and thick beds