ACTA GEOLÒGICA HISPÀNICA t. 18 (1983), nº 1, págs. 47-53

# Discussion about the emplacement of some of the Southern Pyrenees nappes (Spain)

by L. SOLE SUGRAÑES

Instituto Jaime Almera. Alcarria s/n. Barcelona-28, Spain

The Southern Pyrenees or the Prepyrenees as the Spanish geologists use to refer them are one of the main tectonic units of the Pyrennes and extend for more than 600 km from east to west. They separate the cristalline Paleozoic axis to the north of the wide flat expanse of de Ebro basin to the south (fig. 1).

Seguret (1972) and Garrido and Rios (1972) proved that the Pyrenees are formed by superimposed nappes and slices of Mesozoic and Paleogene rocks that glided southward some tens of kilometres. Althoung the allochthonous origin of some of these unit had already been suggested by the earliest geologist working in the Pyrenees (Dalloni, 1913, 1931; Jacob et al., 1927) their point of view was not widely accepted until the middle of the seventies.

Nappe emplacement spans from the Early Eocene to the Oligocene and its mechanism and style of deformation changes throughout the orogenic process (Solé-Sugrañes, 1978 a; 1979). The time of the emplacement and the paleogeographic conditions mark the difference among the nappes and smaller allochthons that forms the Prepyrenees.

Former geologists suggested that the nappes were formed by gravity gliding alone (Van Lith, 1968, Van de Velde, 1967) or by gravity instabilities produced by crustal shortening (Seguret, 1972). Solé-Sugrañes (1979) poited out that some of the earliest small nappes may be formed by gravity gliding of carbonate rocks into a turbidic basin, but the Latte Eocene nappes and décollements involving persasive folding and thrusting of Paleozoic rocks must have been strongly pushed form the back due to crustal shortening.

Structures due to nappe movement and their mechanics are discussed. Development of cleavage near parallel to the sole thrusts beneath and above them suggest a ductile behaviour more likely than a pure brittle behaviour with drastic decrease of sliding friction allowed by high geostatic ratio (i. e. ratio of fluid beneath the thrust plane to normal stress on that plane owing to the weight of the overburden). But fracture has to occur because finite shear deformation shown near the thrust planes is too small to support displacement over 30 km. Gravity as a driving force for nappe sliding is examined with restrictions imposed by the acceptable critical slope and development of minor structures.

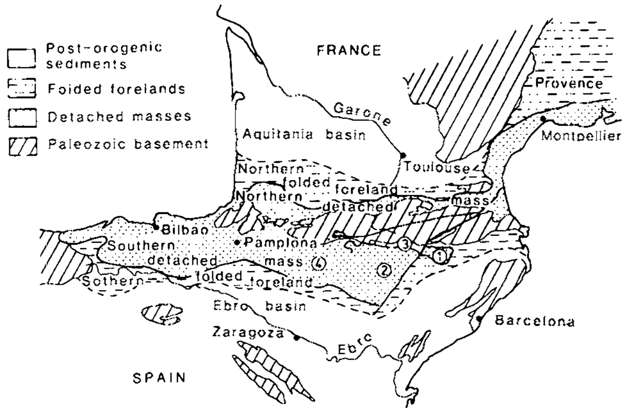

Figure 1.– Main structural units of the Pyrenees. Detached units of the Southern Pyrenees: 1, Pedraforca nappe; 2, Montsec unit; 3, the plunging "noses" of the Nogueras zone and 4, the Central Detached unit.

The allochthons of the Southern Pyrenees can be divided into three differents models according their mechanics of formation: (i) gravity submarine slices as the Early Eocene Cotiella and Monte Perdido nappes, (ii) combined gravity and compresive nappes as the Pedraforca nappe and (iii) décollements and thrusts involving Paleozoic rocks of the basement as the Gavarnie nappe, the Central Detached unit or the Ripoll Thrust.

## THE COTIELLA NAPPE

The Cotiella nappe is one of the first allochthonous units described in the Southern Pyrenees (Dalloni, 1913) and consists mainly of a thick sequence of Upper Cretaceous and Paleocene and Eocene Limestones that rest over the Lower Eocene turbidites of the Central unit between the Cinca an Esera upper valleys.

Allochthonous Cretaceous rocks can be related to the platform and talus facies of a Northern Pyrenean flysch basin white Ilerdian Alveolina-limestones and marls belong to a carbonate platform north to the Jaca flysch basin. Beneath the nappe, Cretaceous roks are of Southern Pyrenean affinity (carbonate and sandy internal platform) overlain by the Eocene turbiditic sequence of the Jaca basin.

Upper Ilerdian and Cuisian strata cover the leading front of the Cotiella nappe (Soler and Garrido, 1970). These strata unconformably overlap Ilerdian flysch in both the Cotiella nappe and its relative autochton south of Peña Montañesa. But the angular unconformity disapears a few kilometres away from the Cotiella front and shallow water deposits rest conformably on the older flysh eleswere even overlying the nappe itself.

The uncorformable Cuisian strata grade to the north and east into increasingly proximal facies of the Montanyana Group deltaic complexe (Puigdefábregas, 1975), but marine deposits grade into conformable, deeper water sediments south and west of the leading edge of the nappe. The Lower Cuisian unconformity is largely restricted to an area adjacent to the nappe front. These facts suggest that Cotiella nappe moved into a marin sedimentary basin without undergoing much internal deformation.

Garrido (1972) suggested that the Cotiella nappe to as Montsec nappe, that included in a single nappe the Montsec and Pedraforca units. The idea of a single allochthon unit including the Cotiella, Montsec and Pedraforca was also hold by Fallot (in Jacob et al. 1927), Seguret (1972) and Choukrone and Seguret (1973) that referred to it as the Central South Pyrenean Unit. But this idea can not be supported because the ages of emplacement of the Cotiella, Montsec and Pedraforca can not be the same. Garrido (1972) suggested that Lower Cuisian strata unconformably overloap the Montsec Thrust fault, but this point of view is unlikely from a minucious study of Ilerdian sedimentary conditions in the Conca de Tremp and Vall d'Ager (Gaemers, 1974). The visible thrust fault along the southern slope of the Serra del Montsec can not represent the main boundary of an allochthon sheet but rather a secondary thrust fault probably related to a latter folding episode. In an oil well near Isona Jurassic and Cretaceous rocks of the Montsec were found overlying Priabonian blue marls pointing aout a limit age for the emplacement of this allochthon.

Solé-Sugrañes (1972) found Upper Eocene rocks (probably "Biarritzian") unconformably overlaping Lutetian marls of the leading edge of Pedraforca nappe that suggest that the emplacement of this unit must be of Late Middle Eocene Age.

Between the Cinca and Esera valleys the Cotiella nappe rest upon younger Cretaceous and Eocene strata and this limits can be easily traced, buy east of the Sierra Ferrara the southern limit is hidden by the syntectonic Cuisian roks that unconformably overlap the Cotiella thrust fault further west.

East of Esera valley there is not visible anomalous superposition over younger rocks. The Jurassic and Cretaceous sequence overlie Triassic evaporites that directly rest on the Paleozoic basement. But there is not a clear eastern limit of the Cotiella allochthon and it is possible that it have never been disrupted from the whole mass of the Montsec Unit. The minimum southward displacement of the allochthon resting on younger rocks is of some 15 km.

Two hipothesis can be suggested to explain the geometry of the Cotiella nappe and its relationships with the Montsec unit: (i) the movement of the nappe could have been accompanied by a slight anticlockwise rotation without any important disruption between the Cotiella rocks and their eastward prolongation into the Montsec unit; or (ii) the Cotiella and the Montsec units form a single allochthon but its movement have took place alt least into two different episodes. The unconformity over the Cotiella fault would be a remainder of the first episode at the end of the Ilerdian time but a latter movement must have took place at the end of the Eocene because Upper Eocene marine rocks occur under the Montsec unit at Isona. The southern limit of this unit must be in the "Sierras marginales" (i.e the contact between the allochthonous units and Ebro basin).

The Cotiella sole fault cuts through the Cretaceous sequence at the back of the nappe and parallel to the strata to the south. At the rear edge of the nappe the contact with its relative autochthon lies within the Upper Cretaceous sequence, while Senonian Limestones overthrust Eocene strata at the leading edge. A narrow band of Eocene marls beneath the sole fault of the Cotiella are cut by near horizontal or gentely south-dipping cleavage. This cleavage can hardly be related to the more ubiquitous north-dipping cleavage that occurs in the marly and pellitic rocks near the contact with the Axial Zone.

No folds or other penetrative structures can be related to the earliest movement of the nappe, except a heading anticline in the leading edge of each slice (fig. 2) and some mega-tension-gashes and normal faults taht occur in the back half of them.

The east-trending fold that bend the trust planes and the north-dipping cleavage that cuts across them must be related to a younger tectonic event probably of Late Eocene age, since strata of this are also folded about east-trending axis.

## THE PEDRAFORCA NAPPE

The Pedraforca nappe extends about 60 km east of the Segre fault and it is formed by a 3 km thick seuquence of Jurassic and Upper Cretaceous marls and limestones that overlies strongly deformed Triassic evaporites and is in turn overlain by a thin Peleocene and Lower Eocene suquence of Garumnian facies and Alveolina-limestones. The strongly folded Pedraforca rocks completely rest on slightly deformed marls and flysh (Bagà Marls and Campdevanol flysh) of Middle Eocene age. Seguret (1972) proved the northern origin of this unit and its minimum southward thrust is of the order of 25 to 35 km (Solé-Sugrañes, 1978 a).

The Cadi thrust fault is the northern boundary of the nappe. It dipps about 45° to the south and brings the Jurassic and Cretaceous rocks over the Eocene strata of the Cadi Sequence. The thrust plane is almost parallel to the Eocene bedding and a 200 m thick detachment layer of Upper Triassic gypsum and purple pellites (Keuper facies) separates the allochthon from the autochthonous substratum.

The southern and eastern boundaries of the nappe are not as well exposed, because they are usually covered by the overlaping Upper Eocene Berga conglomerates (Solé Sugrañes, 1972). The Berga conglomerates rest directly on the Vilada Lutetian marls, which are of the same age as Bagà Marls, the unit inmediatly below the Cadi Thrust fault. Moreover, the fossils in the Sant Llorenç Marls near the bottom of the Berga conglomerates suggest a "Biarritzian" age (late Middle Eocene). So the emplacement of the Pedraforca nappe must have finished at the late Middle Eocene.

Olistostromes of Alveoline-limestones and Triassic rocks included in the last 1000 m of Middle Eocene flysch of the Cadi sequence (Armancies fm. and Campdevanol flysch) suggest that the displacement of the Pedraforca nappe spans over the entire time necessary for the deposition of the turbidities, probably most of the Lutetian age.

Strata in the Pedraforca nappe are folded by broad, upright northeast trending folds. These folds are refolded by younger east-trending folds, and their disappear beyong the unconformity of the Berga conglomerates. Axial-plane cleavage occurs in the pellitic layers of some of these folds. Cleavage is spaced and fan shaped and even thoungh it occurs over the entire unit there is preferentialy well developped close to the southern edge.

The less competent rocks are strongly deformed in a narrow strip only some tens of metres in width above and beneath the thrust plane. Deformation includes well developed south-dipping cleavage nearly parallel to the thrust plane and drag folds. These folds are asymetric, with short south-limbs and north-dipping axial-planes.

The folds have a wavelength of from less than one metre to a few metres. In certain places it is difficult to stablish a clear relationship between cleavage and drag folds, although cleavage surfaces cut across both limbs of certain folds. Even the orientation of the fold axis is very variable in a short distance. Some of the folds are obviously drag folds in the friction zone between the both units, but others could be older slumps rotated during the displacement of the upper unit.

East of the Segre fault, east-trending north dipping cleavage is restricted to the Cadi sequence and its upper front usually lies a few hundred metres north of the Cadi thrust fault. Where the front closes the base of the nappe the south-dipping cleavage is intersected by north-dipping cleavage (Bastareny valley). The time relationship of the devolopment of both cleavages is not clear from outcrop information and it has to be explained from regional insight.

Small slices of Paleozoic and Lower Eocene limestones overthrust Eocene flysch along the contact with the Axial Zone east of the Pedraforca nappe. The slices are folded along east trending axis. The folds have north-dipping axial-plane cleavage with cuts across the thrusts planes of the slices bearing only Eocene, but which lies nearly parallel to the sole faults of the slices bearing Paleozoic rocks.

The thrust planes bounding the slices bearing Eocene affect Lutetian rocks and must have been active at about the same time as the Pedraforca sliding. Refolding of these slices, thrusting of the Paleozoic rocks over the Eocene flysch and development of cleavage obviously occured during a leter phase of deformation. The axial-plane cleavage of these folds is continous wiht the nort-dipping cleavage that intercepts the cleavage parallel to the Pedraforca thrust fault in the Bastareny valley.

## THE GAVARNIE NAPPE

The Gavarnie nappe is one of the largest allochthonous units bearing a core of Upper Paleozoic rocks that overthrust the autochthonous (or parau-tochthonous) sedimentary cover of the Axial zone in its southern margin. The emplacement of these units affecting the Hercynian basement must be related to the Late Eocene tectonic events.

Late Eocene deformation extends over the entire Southern Pyrenees and several prograding unconformities on the molasa deposits (Riba, 1967) indicate that no single phase of deformation ocurred during the Late Eocene and Early Oligocene, but deformation took place in a sequence of discrete events some of only local significance (Solé-Sugrañes, 1978 a).

At the of the Eocene main tectonic events inlude east-trending folds and thrusts, the emplacement of the Paleozoic-bearing Gavarnie nappe and Nogueras units, the décollement of the Central Detached unit and the thrust of the Cadi unit.

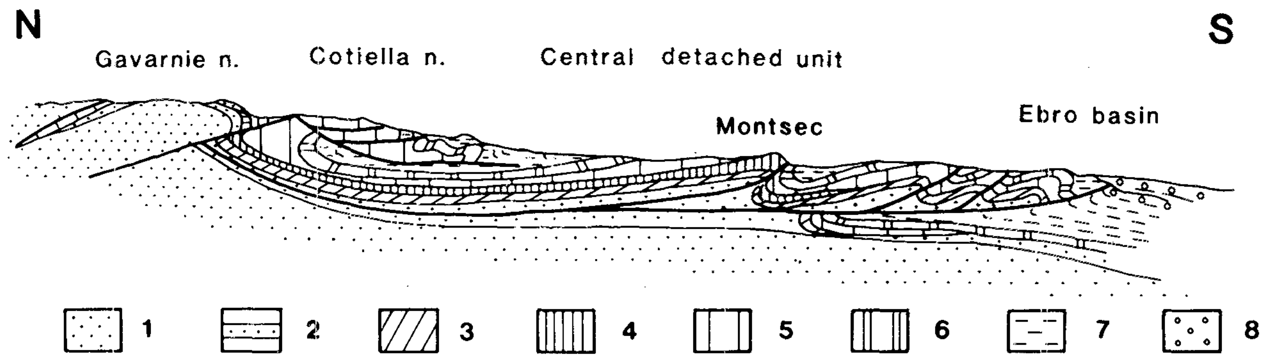

Figure 2. Cross section of the Central detached unit. 1, Paleozoic basement rocks; 2, Permotriassic molassa, volcanic rocks and upper Triassic evaporites; 3, Jurassic; 4, Lower Cretaceous; 5, Upper Cretaceous; 6, Eocene Alveoline bearing limestone; 7, Middle Eocene marls and flysch; 8, Upper Eocene and Oligocene molassa.

The southward thrust of the Peleozoic core of the Gavarnie nappe is of 9 km at the Gavarnie vindow but al least of 15 km at Bielsa a few kilometres to the east (Seguret, 1972). Flat east-strinking cleavage occurs in the autochthonous Cretaceous limestones beneath the thrust fault. The cleavage passes to the adjacent Paleozoic rocks bending up to north-dipping. Flat to north-dipping cleavage also occurs in Triassic and Cretaceous strata that outcrop below the Paleozoic overthrusting rocks at Bielsa, Punta Suelza, Bergasera, Eaux Chaudes, Bac-Grillera, Costouges, etc. and may be related to the more obicuos axial-plane cleavage of east-trending folds that occurs in the northern margin of the Prepyrenees.

The Paleozoic core of the Gavarnie nappe terminates a few kilometres south of Gavarnie but its Mesozoic and Tertiary cover was detached from its basement and southward overthrusted. The basal thrust fault must step up from inside the Paleozoic rocks to the Upper Triassic evaporitic horizon located between the Hercynian basement and the Alpine sedimentary cover.

Part of the southward displacement of this detached cover may be compensated by folding and subsidiary thrusting, but shortening by internal deformation within the allochthon is not enough to compensate for the stimate offset of the northern edge. The sole fault may emerge in the "Sierras marginales" in the northern margin of the Ebro basin or may be partially covered by overlaping Upper Eocene and Oligocene conglomerates. Minor folds and reverse faults, some of oligocense age, are common in the "Sierras marginales" making it difficult to determinate if the main fault actually emerges there.

The detached sedimentary cover is folded about east-trending axis. A few isolated south-facing anticlines (Montsec, Boixols, Sant Mamed) occur separated by ill-defined large synclinal areas. However south-facing folds of Late Eocene or Oligocene age are pervesive over the entire Southern Pyrenees and they refold older folds (Northeast-trending folds in the Pedraforca nappe area) and the sole faults of the Cotiella, Monte Perdido, Pedraforca nappes and other minor slices. Close to the Axial Zone these folds are associated with axial-plane cleavage that dips to the north. Formation of these folds must be related to the drag due to the displacement of the detached cover but others must be formed by a north-pushing mass related to crustal shortening and overthrust of the Paleozoic-bearing units.

## DISCUSSION

Southern Pyrenees nappes can be divided into three different models according to their mechanics of formation. The Cotiella nappe as a probably pure gravity slice and the Gavarnie nappe as a typical a recumbent fold with the basement involved in its core might be considered the extreme models. The Pedraforca nappe might be of an intermediate type between them.

Folding or internal deformation are absent or restricted to a minimum in the Early Eocene Cotiella nappe. This nappe appears to be formed by thin slices of the sedimentary cover detached from the upper part of the continental talus and glided into a turbiditic sedimentary basin over a surface of low frictional resistence.

Gravity due to uplift of the basement in the Axial zone have probably caused the sliding movement. Normal faults in the continental talus could have minimized the toe effect and facilitated pure gravity sliding. No data about the slope of the original thrust planes are avalaible because of refolding, erosion and parcial overlapping of nappes by syntectonic sediments. Imbrication of slices within the units can either be due to the original gravity sliding or to later refolding.

On the other hand, the persasive folds with axial-plane cleavage that effect both the sedimentary cover and its Paleozoic basement clearly point to crustal shortening and consequent tectonic pushing as a driving mechanism for the Gavarnie thrust and the décollement of the Central detached unit.

The isolated asymetric anticlines separated by large ill-defined syncline areas suggest that gravity sliding played an important role in the mechanics of movement of the Central detached unit. A cross section of this unit (fig. 2) looks very similar to the plasticine models developed by Blay et al. (1977). Pervarsive folding with north-dipping axial plane cleavage obviously points to tectonic pushing in the Gavarnie nappe and in the rear half of the Central detached unit. But part of the deformation in the leading half of the detached unit must have been caused by drag friction resistence to the gravity sliding.

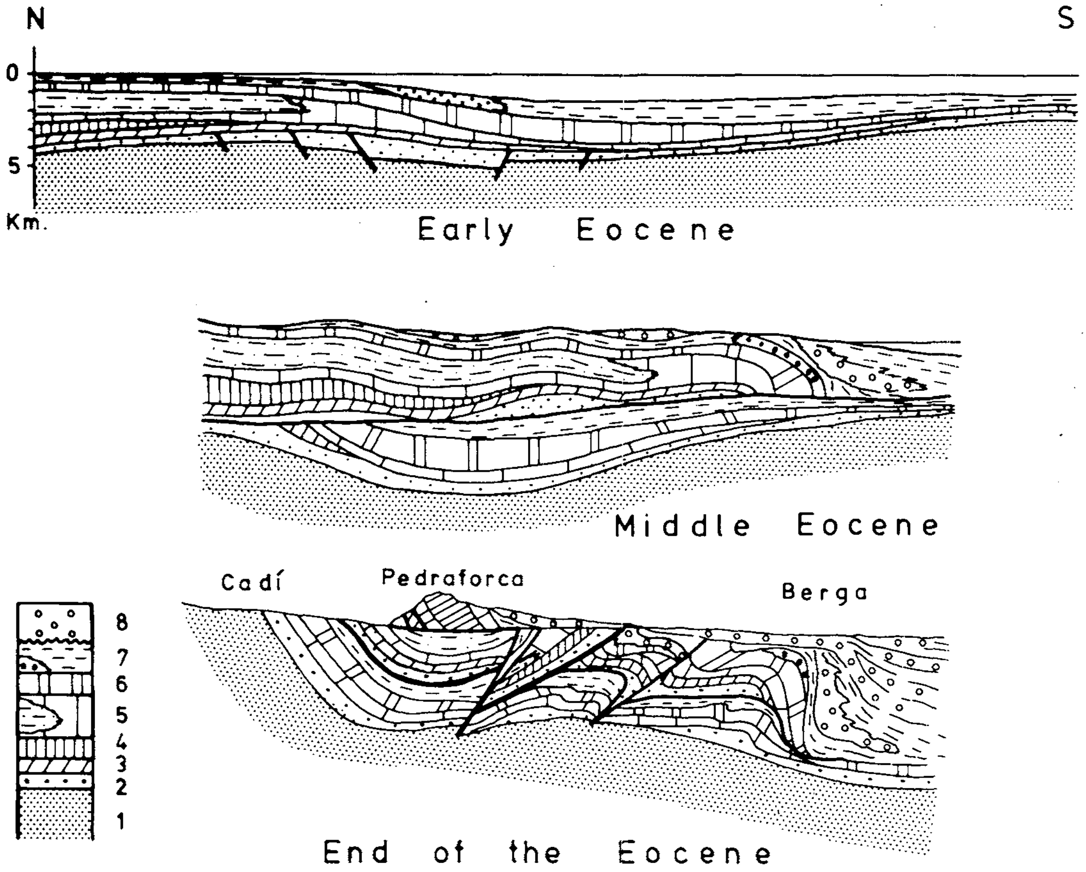

Figure 3.·· Eocene evolution of the Pedraforca nappe. Lithological symbols are the same as in fig. 2, but in the Upper Cretaceous (5) limestones and marly units have bean differenciated. The Queralt conglomerates (probably a wild flysch formation) have also been differenciated in the marly and flysch Eocene formations (7).

Also the resistance to the downslope movement that the sediments shed from the leading adge of the advancing mass offered would certailny have contribued to the folding of this unit. However the relative importance of the different forces involved cannot be established from the data avalaible.

The Pedraforca nappe is of an intermediate type between the Cotiella and the Gavarnie nappes. As in the Gavarnie nappe northeast-trending folds could be related to tectonic pushing, but cleavage developed preferently in the leading edge of the nappe rather than in its rear part. As the Cotiella and Monte Perdido slices the Pedraforca nappe slid into a marine sedimentary basin. However fluvial sediments that overlap the front of the nappe suggest taht it did not slide into a deep flysch through and that its arrival at the bottom of the basin interrupted marine sedimentation.

### *The Pedraforca model*

The Pedraforca nappe is a 3 to 3,5 km thick slice, which has thrust a minimum of 25 km southward over Eocene shales and turbidites. The water depth of the Eocene sedimentary basin can be estimated as having been a maximum of 2.000 m. The detachment layer at the base of the nappe is formed by a unit of Triassic shales and evaporites of Keuper facies which is about 200 m thick. The cohesive strengh of these materials is low and in dry conditions is of the order of 30 bars. At high pore water presure it is as low as 10 bars (Heard and Rubey, 1966).

Figure 3 sketches the tectonic evolution of this unit. Until the Upper Cretaceous the basement had been plunging to the north and thicknees of sediments increases in this direction. Deeper-water facies and maximum thickness were deposited on the present Axial Zone. At te begining of the Eocene polarity of the sedimentary basin was reversed and until the oligocene maximum thicknees of Eocene limestones, shales and turbidites were deposited on the north margin of the Ebro basin. In the late Middle Eocene the Pedraforca nappe, which decolled over an intermediate Triassic evaporite layer, thrust over the Eocene strata a minimum 25 km southward. Upper-Eocene-Oligocene fluvial molasa has overlapped the front edge of the nappe.

At the end of the Eocene, small slices formed by Jurassic and Lower Cretaceous rocks thrustover the Pedraforca nappe. These slices belong to the Montsec or Central detacehd unit according to their stratigraphic affinities and they have glided over an erosion surface that cuts the fold of the Pedraforca nappe (Solé-Sugrañes, 1978 a).

These small units had been located the bakc of the Pedraforca nappe and they were probably still attached to the nappe during its slicing in the late Middle Eocene.

### *Cleavage and folds at the base of the nappe*

A narrow strip of only a few hundred metres in width above and beneath the Pedraforca thrust in strongly deformed. Closely spaced-cleavage occurs nearly parallel to the base of the nappe and the Eocene strata beneath it.

Small scale folds are common in the more pellitic layers near the thrust plane, but they are also apparent in the massive limestone close to the base of the nappe.

The relationship between folds and cleavage is extremely variable. Cleavage is axial plane to some folds in the Eocene strata of the Bastareny valley. However, cleavage can cut across both limbs of some folds or even be bended by younger folds. The plot of the fold axis in a stereographic net shows that they fall into two clusters. One well defined cluster contains west-plunging axis and the other is a wide scattered-cluster that contains southeast-plunging axis. Northdipping cleavage is potencial axial-plane to the west-plunging folds. They must be related to the Late Eocene phase of deformation that develops cleavage that is axial-plane to east-trending folds. The other folds trend approximately to the southeast. The older folds have both limbs cut by the south-dipping cleavage and might have formed by synsedimentary slumping or might be drag folds formed before the development of cleavage. The minor folds with south-dipping axial-plane cleavage are obviously drag folds.

Neither synsedimentary folds in the Eocene strata nor major folds within the Pedraforca nappe trend southeast. Thus some minor folds close to the thrust plane must have been rotated in the direction of the nappe displacement by shear deformation.

Both the development of drag folds and cleavage nearly parallel to the thrust plane and rotation of folds in the direction of displacement, point to shear deformation in the autochthon. A shear zone developed because friction was far from negligible and fluid pressure could not have approached at the weight of the overburden in the thrust plane.

### *Northeast-trending folds*

Large scale northeast-trending folds taht are mainly found in the area of the Pedraforca nappe suggest a close relationship between fold development and the development of the nappe. These folds could have been formed (i) by compressive shortening of the nappe due to tectonic pushing, (ii) by drag friction resistance, or (iii) by resistance in the leading edge due to the bulldozer effect. Development of cleavage preferently in the leading part of the nappe strongly suggest that the folding was caused by the bulldozer effect assisted by accumulation of sediments shed from the leading edge of the nappe.

### *The intermediate model*

The structure described in the Pedraforca nappe lead to the following conclusions and restrictions for any model that tries to explain the conditions under which it was formed.

Cleavage and drag folds in the trust zone as well as major folds within the nappe related to its movement suggest that friction over the thrust plane was not drasticly lowered by a high geostatic ratio.

The nappe slid over the margin of a flysch basin that was less than 2.000 m deep. The maximum slope that can be reasonably accepted for the margin of the flysch basin is of the order of 2 to 4 degrees. The base of the Pedraforca nappe exposed along the Llobregat river suggest an original slope about 2 degrees.

Slopes of this order are compatible with underwater sliding conditions allowing a minimum lenght of 30 km for the Pedraforca unit and re-establishment of marine sedimentation over a major part of it, a short time after nappe emplacement.

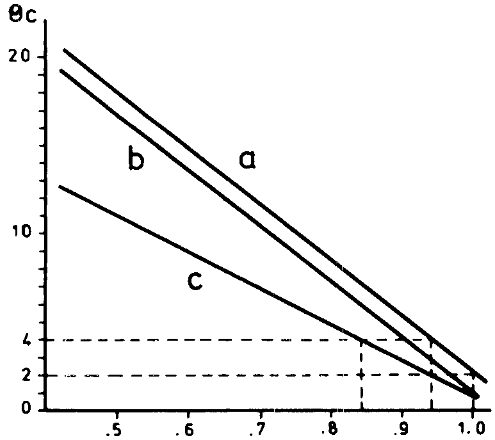

Figure 4.– Computed critical slapes for gravitational gliding (see text).

In figure 4 the critical slope for gravity sliding has been computed for cohesive stregths ranging 10 to 30 bar and angles of internal friction from 10 to 30 degrees. These values are of the same order as those suggested for evaporitic masses by Heard and Rubbey (1966) and Hsü (1969). A critical slope for gravity sliding is reached when the shear stress at the base of the allochthon has a minimum value of:

$$\tau_c = \tau_0 + \rho\, gz\, (1 - \lambda)\ \mathrm{tag}\ \phi_i \cos \theta_c$$

where $\tau_0$ is the cohesive strength, $\rho$ the density, g aceleration due to gravity, z the thickneess of the allochthon, $\lambda$ the geostatic ratio, $\phi_i$ the angle of internal friction and $\theta_c$ the chritical slope.

From these data gravity sliding is only possible for slopes lower than 4 degrees if the geostatic ratio is over 0.85 and without taking frontal resistence to the downslope movement and the toe effect into account. So it can be concluded that it is very unlikely that the Pedraforca nappe was formed only by gravity sliding.

Kehle (1970) suggested that thrust can develop by shear deformation of a décollement layer without faulting. The Triassic evaporites at the base of the Pedraforca nappe were certainly deformed in a ductile way. But if only shear deformation was responsable for a minimum thrust of 25 km shear strain would have to take values of over 300 for an original one kilometre thick plastic layer. Values as great as that have never been described and in spite of the deformation the sedimentary feactures are still very well preserved.

Furthermore critical values of the deviatoric stress for Anderson-type britle failure (Sibson, 1977) are reached at the base of the Pedraforca nappe even for low geostatic ratios and high internal friction angles.

All these data point to the existence of a bedding fault at the base of the nappe, and that gravity assisted by tectonic pushing due to crustal shortening have been the driving mechanisms that made the thrust of the Pedraforca nappe possible.

If this was so, this northwest compression event was not only significant at local level but it could have been a general tectonic feature at the end of the Middle Eocene in Northeastern Spain as is suggested by fault movements in the Catalanid ranges (Solé-Sugrañes, 1978; Guimerà and Santanach, 1978).

## REFERENCES

BLAY, P., COSGROVE, J.M. and SUMMERS, J.M. 1977. "An experimental investigation of the development of structures in multilayers under the influence of gravity." *Jl. Geol. Soc. of London*, 133; 329-342.

CHOUKRONNE, P. and SEGURET, M. 1973, "Tectonic of the Pyrenées: role of compression and gravity". *in* D. Jhong and R. Sholten eds. *Gravity and Tectonics.* New York, John Wiley & Sons, p. 141-156.

DALLONI, M., 1913. "Stratigraphie et tectonique de la région des Nogueras (Pyrenées Centrales)". *Soc. Geol. Fr.* 13: 243-263.

DALLONI, M., 1930. "Etude géologique des Pyrenées Catalans". Ann. Fac. Sci. Marseille. 26: 373 p.

GAEMERS, P.A.M., 1974. "A study of Lower Tertiary stratigraphy, paleogeography and tectonics in Spanish Pyrenees". *Konikl. Nederl. Akademie Van Wetenschap pen-Amsterdam.* 77 (3): 246-258.

GARRIDO-MEJIAS, A and RIOS, L.M. 1972. "Síntesis geológica de Pedraforca y sus consecuencias: una nueva unidad tectónica independiente "el manto del Montsec". *Bol. Geol. y Minero.* 84: 303-311.

GARRIDO-MEJIAS, A and Ríos, L.M. 1972. "Síntesis geológica del Secundario y Terciario entre los ríos Cinca y Segre". *Bol. Geol. y Minero*, 83: 1-47.

GUIMERA, J. y SANTANACH, P., 1978. "Sobre la compresión alpina en el sector central de las Cadenas Costeras Catalanas." *Acta. Geol. Hisp.* 13 (2): 33-42.

HEARD, H.C. and RUBEY, W.W., 1966. "Tectonic implications of gypsum dehydration". *Geol. Soc. Am. Bull.*, 77: 741-760.

HSÜ, K.J., 1969. "Role of cohesive strengh in the mechanics of overthrust faulting and landsliding." *Geol. Soc. Am. Bull.*, 80: 927-952.

JACOB, CH., FALLOT, P. ASTRE, G. et al., 1927. "Observations tectoniques sur le versant méridional des Pyrenées centrales et orientales". *Int. Geol. Congr. 14th.* Madrid. Comptes rendues. 2: 335-412.

KEHLE, R.O., 1970. "Analysis of gravity sliding and orogenic translation." *Geol. Soc. Am. Bull.*, 81: 1641-1664.

RIBA, O., 1973. "Las discordancias sintectónicas del Alto Cardener (Pirineo Catalána) ensayo de evolución interpretativa". *Acta Geol. Hisp.* 8: 90-98

SEGURET, M., 1972. *"Etude tectonique des nappes et séries decollées de la partie centrale du versant sud des Pyrénées.* Toulose. Univ. Sci. Tech. du Languedoc. Pub. *2, 155 p.*

SOLE-SUGRAÑES, L., 1972. "Nota sobre una discordancia en el Eoceno medio del Pre-Pirineo oriental". *Acta Geol. Hispánica*, 7 (1): 1-6.

SOLE-SUGRAÑES, L., 1978, a. "Gravity and compressive nappes in the central southern Pyrenees (Spain)". *Am. Jl. Sci.* 278 (5): 609-637.

SOLE-SUGRAÑES,.1978, b. "Alineaciones y fracturas en el sistema Catalán según las imágenes LANDSAT-1." *Tecniterrae* 22: 1-11.

SOLER, M. and GARRIDO, A., 1970. "La terminación oriental del manto del Cotiella". *Pirineos*, 98: 5-12.

Recibido, abril 1982