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SHORT NOTE

Tectonic wedges: geometry and kinematic interpretation

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Abstract—The geometry of several tectonic wedge combinations was studied in an outcrop in the Basque Basin, Western Pyrenees. Three types of tectonic wedges were distinguished: simple, double and triple wedge. On the surface the geometry of the observed tectonic wedges is always highly elemental: emergent thrust, horse or klippe.

The final stage in the evolution of a tectonic wedge is its delamination. This can occur by the spreading of the thrusts which conform the wedge, or by the development of back thrusts associated to them. The relative age of the back thrust with respect to the thrust indicates whether the original structure was a simple thrust or a tectonic wedge. If this criterion is applied to the Pyrenean Orogen, this range corresponds to a tectonic wedge.

INTRODUCTION

ACCORDING to Price (1986), a tectonic wedge is 'a structure that is bounded at its roof and floor by shear surfaces or thrusts with opposing vergences', that merge along an intersection line. Tectonic wedge development has been modelled experimentally by Paterson (1958) who found that in rigid-plastic conditions in experimental cylinders, fractures developed along conjugate systems of planes. The first description of a structure corresponding to a tectonic wedge is the 'intercutaneous thrust' of Fallot (1949). Oxburgh (1974) modelled a tectonic wedge which caused a delamination to explain the process of obduction. Other terms that can also be considered for tectonic wedges are: blind thrust (Thompson 1979); buried thrust front (Morley 1986); triangle zone (Jones 1982, Washington 1987); and passive-roof thrust associated to a blind thrust (Bank & Warburton 1986).

Since wedges develop along conjugate fractures, many geometric shapes can be generated. Geometrically, tectonic wedge combinations are a system of conjugate thrusts with opposite dip and vergence that develop as a continuous plane. According to the number of tectonic wedge sub-units they can be called simple, double or triple wedges (Fig. 1).

The evolution of the thrusts in a tectonic wedge, can generate associated structures, such as delamination (Fig. 2d) or back thrusts (Fig. 3). In some of the wedge combinations observed, the geometry can be very complex, depending on the ramp lengths and the position of wedge segments with respect to each other (Fig. 4). However, on the surface the geometry of such structures is always very simple, outcropping as a single thrust (Figs. 2a–c; and 4), a horse (Fig. 3) or a klippe (Fig. 2d).

Tectonic wedges are found in practically all orogens. Simple tectonic wedges have been described in the Alps (Laubscher & Bernoulli 1982), the Canadian Cordillera (Jones 1982, Tirrul 1983, Price 1986), the Moroccan Rif (Morley 1986), Pakistan (Banks & Warburton 1986,

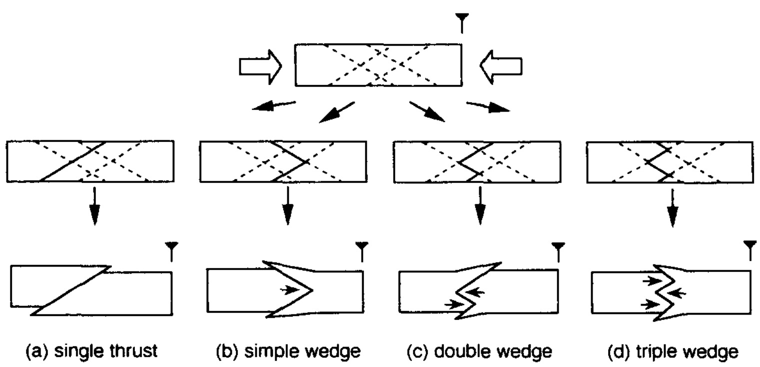

Fig. 1. Potential conjugate shear surfaces (top) and some possible combinations of tectonic wedges.

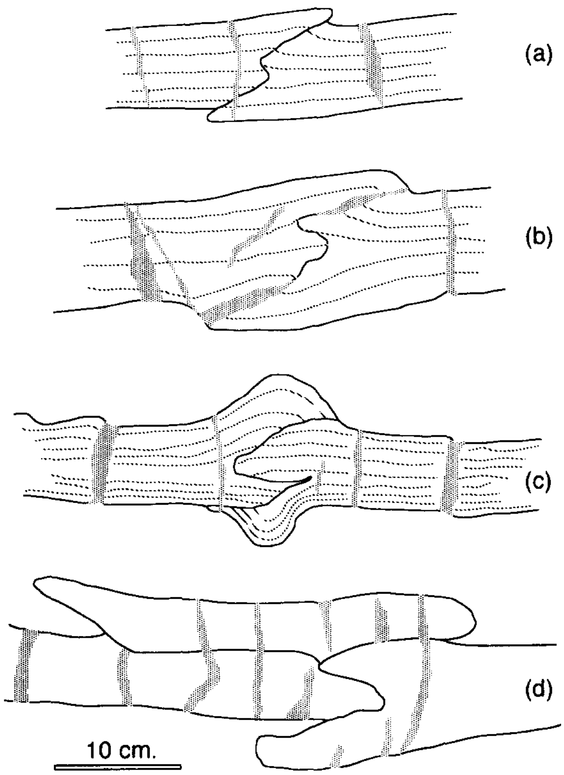

Fig. 2. Sketches of different types of double tectonic wedges (a–c) with progressively greater shortening in the Basque Basin outcrop. In (d) a delamination developed. The shortenings measured between the lower and upper tiplines of the thrust are: (a) 6%; (b) 12%; (c) 26%; (d) 46%. Dotted areas are calcite filled fractures.

Humayon *et al.* 1991), the Andes (Ramos 1989, Allmendinger *et al.* 1990), California (Unruh & Moores 1992) and the Caribbean (Russo & Speed 1992). The classical Alpine structure of Ivrea Body (Ménard & Thouvenot 1984) can be considered as a double wedge and the structure described by Suppe (1983) in the Taiwan Thrust belt associated with duplex systems, is the geometry which would correspond to that of a triple wedge.

A KINEMATIC ANALYSIS OF TECTONIC WEDGES IN THE BASQUE BASIN

The geometry and kinematic significance of several combinations of tectonic wedges found at the sea port of Astondo in Gorliz have been studied in detail. The outcrop studied is situated in the central part of the Basque Basin of the Western Pyrenees (northern Spain).

The tectonic wedges occur in the base of a calcareous flysch of Upper Cenomanian–Coniacian age (Mathey 1983). Four centimeter-thick levels of limestone and calcarenite, embedded in decimeter-thick levels of black marl, can be observed along an outcrop of 100 m long and 15 m wide. The layers are subvertical trending N80E and belong to the northern limb of a north-verging fold. The tectonic wedges develop in the competent layers.

All the theoretical tectonic wedge combinations presented in Fig. 1 are observed in the outcrop studied. Several stages in wedge evolution can be recognized for each type of wedge, which allows reconstruction of the development of these structures. Our interpretation of the observed structures is that tectonic wedge development involves deformation under rigid-plastic conditions in the competent levels, and subsequent development of a single thrust surface with Z or S shape on conjugate shear planes (Fig. 1).

A single tectonic wedge (Fig. 1b) is formed by a floor and roof thrust segment which define a buried thrust front intersection. Wedge kinematics involves migration of this buried thrust front. Tectonic wedge combinations (Figs. 1c & d) develop by the progressive migration of the tiplines of each wedge. In double tectonic wedges the tiplines usually separate progressively (Fig. 2) although they may get closer in some cases (Fig. 4).

The double wedge (Fig. 1c) is the most widely represented structure in the outcrop studied. Several double tectonic wedges with different degrees of evolution are found (Fig. 2). In the cases considered, we can see that the tiplines of each wedge are progressively

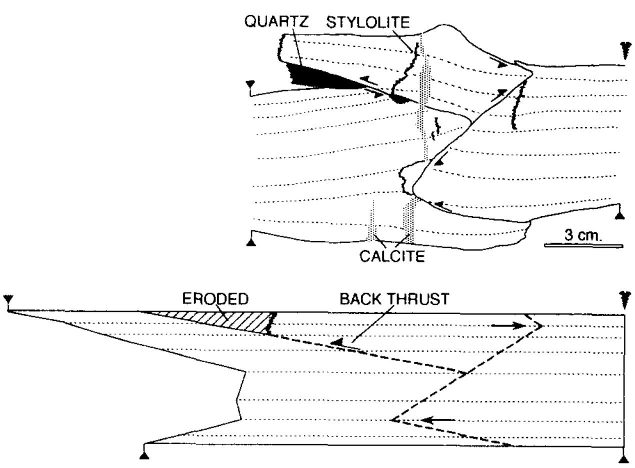

Fig. 3. (a) Field example of a double tectonic wedge with an associated back thrust; (b) balanced cross-section. With the chosen tipline, all the longitudinal deformation accumulates in the block at left.

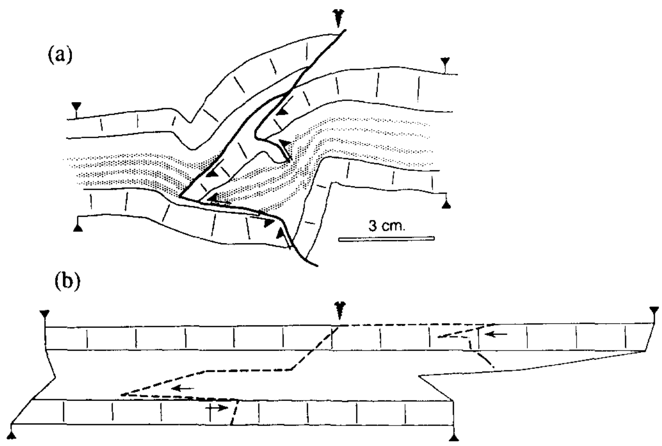

Fig. 4. (a) Triple wedge example with penetration of the upper wedge in the lower one; (b) balanced cross-section. The longitudinal deformation is concentrated in the incompetent levels and, to a certain extent, in the more competent calcareous levels.

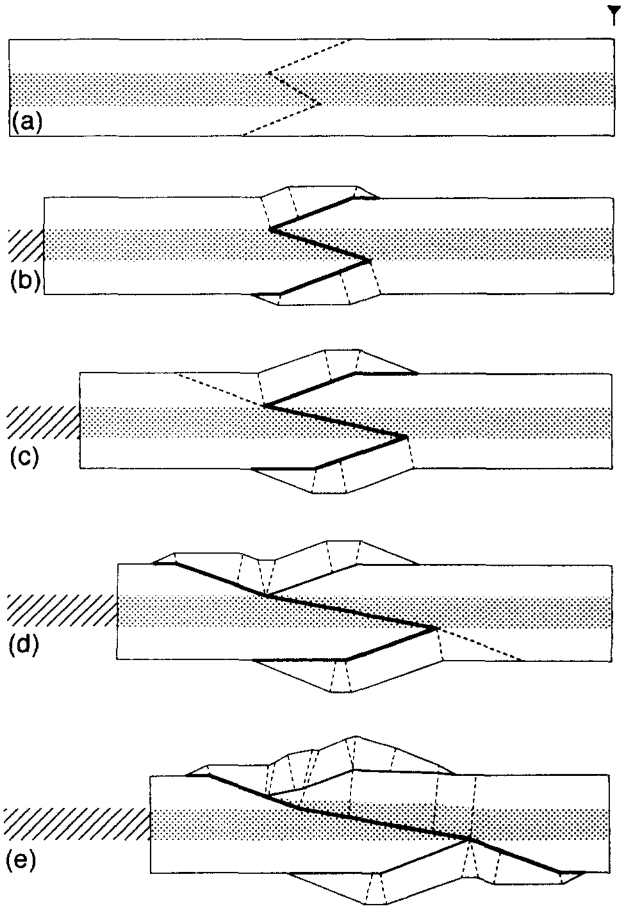

Fig. 5. Kinematic evolution of a double wedge until roof delamination (d) and floor delamination (e) take place. The central area (striped) is not balanced and interpreted to accumulate deformation by bedding-parallel shear in the incompetent levels. The bold line indicates active fault surfaces.

separated as the structure develops. This separation implies propagation of the thrust plane common to both wedges (Figs. 2a–c). Finally, the development of tectonic wedges stops as delamination evolves (Fig. 2d).

The different degrees of evolution observed in the outcrop permits a kinematic analysis of tectonic wedges. In the kinematic model proposed (Fig. 5) there is a non-balanced area that is interpreted to accumulate deformation by bedding-parallel shear in the incompetent levels. Moreover, there might be a pure shear component depicted by the thickening and dip increasing of the planes that conform the tectonic wedges, such as is observed in the study area (Figs. 2a–c).

The last stage in development of tectonic wedges is delamination (Figs. 5e & d). The tectonic wedge then loses its original geometric characteristics and turns into an emerging thrust with an associated back thrust that defines an alochthonous unit, i.e. a klippe (Fig. 5d). An identical process occurs in the lower wedge (Fig. 5e). The final state of a double wedge, after the generation of the delamination on the upper and lower wedges, is a thrust limited at its roof and floor by two décollement sheets (Fig. 5e).

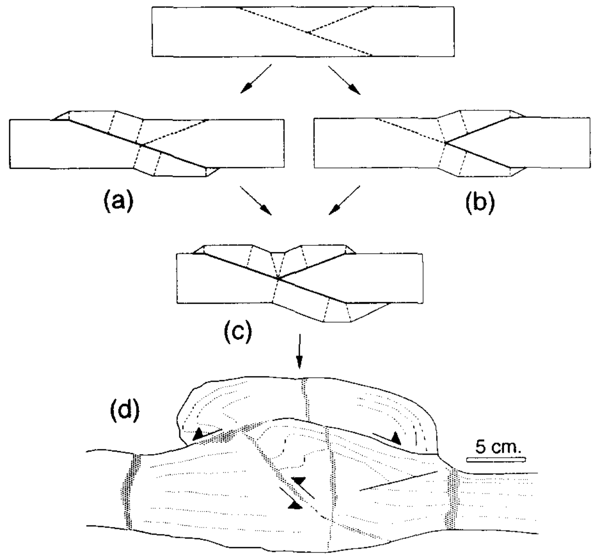

Fig. 6. Delamination is the last stage in tectonic wedge evolution. It may develop by: (a) a back thrust initiating from a forward thrust; or (b) propagation of a forward thrust to the roof thrust. The final structure is identical (c). However, in case (a) the resulting back thrust is younger than the main thrust whereas it is older in case (b). (d) Cross-section of a natural example with delamination and 53% shortening between tiplines, that may have formed by (a) or (b). The dotted areas are calcite filled fractures.

Delamination of a tectonic wedge

A delaminated unit can be generated from two different structures (Fig. 6). It may form by development of a back thrust (Fig. 6a) or by the propagation of the floor thrust of a simple tectonic wedge towards the roof (Fig. 6b). In either of the two possibilities, the resulting cross-section is identical and can be defined geometrically as a main thrust and antithetical back thrust (Fig. 6c). In order to know which of the two models is correct we have to know the age of the thrusts. In the first model (Fig. 6a) the back thrust is younger than the main thrust. In the second model (Fig. 6b) the back thrust is older than the main thrust.

APPLICATION TO THE PYRENEES

The Alpine range of the Pyrenees is an interesting example of the existence of tectonic wedges at the scale of an orogenic belt. A 200 km long deep seismic reflection profile across the Pyrenees, from the Ebro foreland basin in the South to the Aquitaine foreland basin in the North shows the deep geometry of this orogenic belt (ECORS Pyrenees team 1988).

The profile shows that Iberia is subducted under Europe (Fig. 7c). Geometrically, the cross-section corresponds to an upper unit of thrust sheets which form the Pyrenees s.s, limited at the base by a main thrust emerging in the Sierras Marginales and an emergent back thrust in the North Pyrenean Frontal Thrust. Such a geometry, with a low angle fault within the crust, was already postulated by Fischer (1984) from balanced and

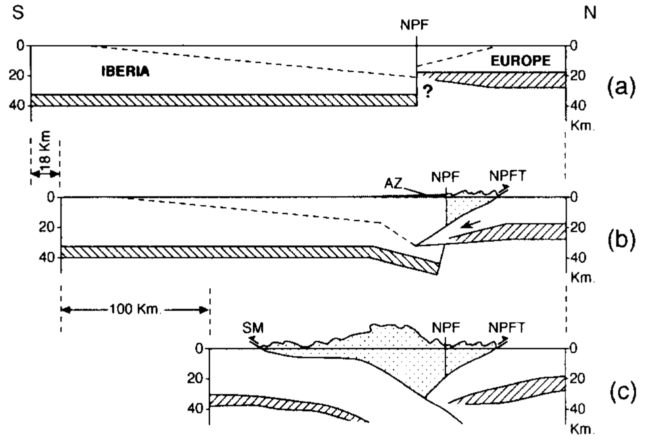

Fig. 7. Schematic model of the structural evolution of the Pyrenees from a simple tectonic wedge (cf. Fig. 6). (a) Section of the geometry prior to collision of the Iberian and European plates; (d) Development of the North Pyrenean Zone previous to that of the South Pyrenean Zone; (c) ECORS profile diagram (from Roure *et al.* 1989). Shortening values have been taken from Desegaulx *et al.* (1990).

restored cross-sections. However, according to Desegaulx *et al.* (1990) the North Pyrenean Zone deformation is older than in the South Pyrenean Zone; therefore the North Pyrenean Frontal Thrust cannot be considered as a back thrust of the South Pyrenean Frontal Thrust of the Sierras Marginales.

The ECORS profile shows that the Pyrenees constitute an upper unit delaminated by the North and South Pyrenean thrusts. The structure that generates a décollement unit can be found from the age of the thrust and its associated back thrust. If we compare Figs. 6 and 7 and accept that deformation in the North Pyrenean area is older than the South Pyrenean area, the Pyrenean Orogen may be interpreted as a large-scale tectonic wedge.

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