Tectonic and sedimentary evolution of the Dévoluy Basin, a remnant of the Tertiary western Alpine foreland basin, SE France

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L'évolution tectonique et sédimentaire du bassin du Dévoluy, un fragment du bassin tertiaire d'avant-chaîne des Alpes occidentales de la France sud-orientale

Géologie de la France, n° 2, 1996, pp. 3-26, 13 fig., 1 tabl., 1 pl. photo.

Key words: Foreland basins, Upper Cretaceous, Tertiary, Alpine orogeny, Tangential tectonics, Hautes Alpes, Devoluy.

Mots-clés : Bassin avant-pays, Crétacé supérieur, Tertiaire, Orogénie alpine, Tectonique tangentielle, Hautes-Alpes, Monts Dévoluy.

Abstract

Upper Mesozoic and Cenozoic sediments preserved in Dévoluy, SE France, record the complex synorogenic evolution of the western Alpine foreland basin at the bend in the external western arc. Periods of active tectonism in the late Mesozoic, early Tertiary, and Mio-Pliocene alternated with periods of orogeny-related sedimentation in the Turonian and late Senonian and the late Eocene through late Oligocene.

E-W to NE-SW oriented pre-Senonian folds of Turonian to Coniacian age are unconformably overlain by up to 700 m of Senonian cherty limestones. Post-Senonian, pre-late Eocene tectonic activity resulted in the formation of NNW-SSE-oriented folds and extensional faults in NE Dévoluy. Locally-sourced continental sedimentation postdates folding, but occurred synchronously with the extensional faulting. This localized deformation and sedimentation is believed to be related to strike-slip displacement along the Aspres-lès-Corps Fault north of Dévoluy, which itself may have been related to pre-Priabonian uplift of the Pelvoux massif to the east.

Upper Eocene Oligocene sediments in Dévoluy document the development of a foreland basin in the external Alpine domain. The basin evolved from carbonate-dominated, transgressive marine conditions during the Priabonian to siliciclastic-dominated, regressive marine and continental conditions from the latest Priabonian through the late Oligocene. Tectonic tilting of the western basin margin accompanied the shallowing. Although this history is similar to that of other fragments of the western Alpine foreland basin, the paleogeography of Dévoluy was complicated by local tectonic activity, particularly on the Aspres-lès-Corps Fault.

Post-depositional Mio-Pliocene folding and thrusting was SW-directed in SE Dévoluy and W-directed in N Dévoluy. A zone of N-S oriented dextral faults occurs where the W-directed Median Dévoluy Thrust begins to steepen and links into the NE-SW oriented, dextral Aspres-lès-Corps Fault. This zone is interpreted as partitioning of regional SW-directed thrusting into strike-slip and thrust components. NE-SW faults with downthrow to the north represent a hanging-wall drop fault zone accommodating the northward stratigraphic climb of the Median Dévoluy Thrust.

Version française abrégée

Le Dévoluy (Hautes-Alpes, France) est l'un des témoins importants de la tectonique crétacée-tertiaire dans l'avant pays de l'arc alpin. Les sédiments d'âge crétacé supérieur et tertiaire de cette région ont enregistré l'évolution complexe des Alpes occidentales externes au Mésozoïque supérieur et pendant le Cénozoïque. Cette évolution comprend : (1) des plis et des failles anté-sénoniens, (2) la sédimentation au Sénonien supérieur, (3) une seconde phase de plis et failles au Tertiaire inférieur, (4) la formation du bassin d'avant-pays des Alpes occidentales dès l'Éocène et, (5) une phase finale de plis et failles au Mio-Pliocène. La faille des Aspres-lès-Corps et le Massif du Pelvoux ont fortement influencé l'évolution puis la déformation de ce bassin.

Des plis W-E à NE-SW traduisent une compression pré-sénonienne N-S à NW-SE. Les épais calcaires sénoniens qui reposent en discordance sur ces plis se sont déposés lors d'une période relativement mal comprise pendant laquelle les profondeurs de dépôt diminuaient. Une déformation localisée, post-sénonienne et pré-Éocène supérieur, est responsable de plis et de failles normales dans le nord-ouest du Dévoluy. Les plis

* Manuscrit reçu le 23 octobre 1995, accepté définitivement le 15 mars 1996.

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sont orientés NNW-SSE et déversés vers l'W: Ils s'amortissent et disparaissent vers le S et sont antérieurs aux conglomérats continentaux de Pierroux.

Des reliefs locaux et une extension existaient lors du dépôt des Conglomérats de Pierroux et des Calcaires Nummulitiques du Dévoluy du NE. Cet événement est enregistré : (1) par la faille normale médiane du Dévoluy, qui fut une faille normale à regard E au Priabonien avant d'être inversée au Mio-Pliocène, (2) par la faille de Lucles, à regard E, (3) par le structure de croissance du Pic Grillon, et (4) par la faille de Pierre Baisse, à regard SW. La localisation de ces structures dans le Dévoluy NE suggère qu'elles sont liées à la faille des Aspres-lès-Corps, active lors de la montée du Pelvoux.

À l'Éocène supérieur et à l'Oligocène, six unités stratigraphiques montrent que le Dévoluy fut intégré au bassin d'avant-pays alpin : le Conglomérat de Pierroux, les Calcaires Nummulitiques, les Marnes du Queyras, les Grauwackes de la Souloise, les Arénites inférieures et les Silts supérieurs de St-Disdier.

Bien que le Conglomérat de Pierroux ne contienne aucun fossile, son âge est stratigraphiquement contraint entre le Maastrichtien supérieur et le Priabonien. Cette unité atteint son épaisseur maximale de 150 m dans le Dévoluy du NE, s'amincit vers le S et l'W pour être stratigraphiquement absente au NW et au SE du Dévoluy. La taille des éléments clastiques diminue vers le SW. Cette formation est dominée par des niveaux de conglomérats épais de 1-5 m, mal stratifiés, à matrice de calcarénite contenant des galets dérivés d'une source locale, sénonienne. Cette formation s'est probablement déposée dans un éventail alluvial avec un dépôt centre au NE.

Les Calcaires Nummulitiques, priaboniens, consistent en deux termes : les conglomérats nummulitiques à la base surmontés par les calcarénites nummulitiques.

Les conglomérats de base, (épais de 1 à 10 m) existent partout sauf dans le Dévoluy SE et NW. Ils atteignent 100 m d'épaisseur au toit de la faille synsédimentaire de Lucles, dans le Dévoluy du N, où ils contiennent de nombreux et gros blocs de calcaire sénonien. Ces conglomérats comprennent deux lithofaciès régulièrement interlités : a) une calcarénite bien triée, à grain moyen et en lits épais de 1 à 100 cm et b) un conglomérat bimodal dont les lits peuvent atteindre 3 m d'épaisseur, à éléments arrondis à sub-anguleux de calcaires et cherts sénoniens dans une matrice de calcarénite. Ces deux lithofaciès contiennent de nombreux fossiles qui indiquent un environnement marin, peu profond, à haute énergie (par exemple, l'avant-côte supérieure, la basse plage ou les bordures des barres tidales peu profondes).

Les calcarénites nummulitiques (1 à 15 m d'épaisseur), partout représentées dans le bassin, sont des « wackestones » ou des « packstones » bien litées (niveaux épais de 10 à 75 cm) avec des clastes arrondis à sub-anguleux. Ce faciès est parfois interlité avec des calcilulites en lits généralement inférieurs au centimètres d'épaisseur. Cette unité est interprétée comme le dépôt de moyenne énergie sur une plate-forme carbonatée à géométrie de rampe. Globalement, les calcaires nummulitiques se sont déposés dans un bassin marin, peu profond mais s'approfondissant.

Les Marnes du Queyras *(Priabonien, 125 m d'épaisseur) sont fortement bioturbées. Elles contiennent de nombreux foraminifères planctoniques et des débris siliciclastiques en quantité variable. Dans leur partie supérieure, une série de lits de grès carbonatés granoclassés, qui enregistrent un apport terrigène, est interprétée comme des turbidites. Les Marnes du Queyras se sont déposées sur une plate-forme ou une pente continentale assez profonde et de basse énergie. Cette formation passe à des sédiments siliciclastiques par l'intermédiaire de boues et silts épais de 25 à 50 m.*

Les Grauwackes de la Souloise *(100 m d'épaisseur), affleurent surtout dans le Dévoluy septentrional. Il s'agit d'une séquence de lits répétitifs, de 1 à 80 cm d'épaisseur, granoclassés depuis des grès à grain moyen ou fin à leur base jusqu'à des silts et boues à leur sommet. Ces lits, attribués à des courants de turbidité diluée et à des tempêtes, se sont déposés sur une plate-forme de moins en moins profonde, peut-être devant un delta. La formation commence sous le niveau de base des vagues et finit au-dessus de ce niveau. Ces dépôts siliciclastiques ont dominé la sédimentation du Priabonien terminal à l'Oligocène inférieur.*

Les Arénites inférieures de St-Disdier *(plus de 125 m d'épaisseur) ne contiennent aucun fossile, mais leur âge est considéré comme Oligocène inférieur (Rupélien). Leur limite inférieure est une discordance progressive le long de laquelle la lacune érosive diminue d'ouest en est, ce qui indique que la bordure occidentale du Dévoluy était suffisamment haute pour être érodée avant ou pendant le dépôt du Rupélien. Cette formation est composée de grès à grain grossier ou fin suivant les endroits, vert ou gris-vert, les lits étant épais de 5 à 150 cm. Les fragments sont constitués de serpentinite et de roches métamorphiques localement abondantes, de quartz monocristallin à extinction droite ou ondulante, de quartz polycristallin, d'orthose, de plagioclase, de micas et de glauconie. Les Arénites inférieures de St-Disdier se sont déposées dans un bassin marin peu profond.*

Les Silts supérieurs de St-Disdier *(plus de 75 m d'épaisseur), datés Oligocène supérieur (Chattien), affleurent seulement dans le Dévoluy de l'W, sous le chevauchement médian du Dévoluy. Ils sont caractérisés par trois lithofaciès dont l'association est typique d'une plaine d'inondation alluviale : a) boues et silts rouges ou vert-rouges, de plaine d'inondation, b) grès verts à grain moyen à grossier, lenticulaires, à granulométrie décroissante vers le haut, qui érodent les boues et silts précédents en une série de chenaux ; c) silts et grès à grain fin, rouges à couleur chamois, avec des nodules calcaires. Ce dernier faciès indique une pédogenèse subaérienne.*

Les facteurs principaux qui contrôlent l'évolution du bassin d'avant-chaîne des Alpes sont tectoniques. Les fluctuations du niveau eustatique de la mer et les vitesses de sédimentation ont aussi eu une influence significative sur le remplissage du bassin. L'étape sous-remplie du bassin est représentée par la transgression marine des Calcaires Nummulitiques et par la sédimentation marine plus profonde des Marnes du Queyras, à l'Eocène supérieur. Le Dévoluy est le témoin le plus occidental et le plus jeune de cette transgression causée par les effets combinés de subsidence tectonique, de failles normales syn-sédimentaires et de la remontée du niveau de la mer, effets qui ont décapé les sédiments à dominante carbonatée.

La transition à des conditions de moins en moins profondes, à l'Oligocène inférieur (Grauwackes de la Souloise), représente le stade de remplissage du bassin, quand l'apport sédimentaire devient plus important que la création d'espace ouvert. Cette transition est due à la combinaison d'une remontée tectonique locale et régionale, d'un apport sédimentaire accru, et de l'abaissement rapide du niveau eustatique. Enfin, le bassin d'avant-chaîne atteint un stade de sur-remplissage, comme en témoignent les conditions marines peu profondes puis continentales à l'Oligocène supérieur (les Arénites inférieures de St-Disdier et les Silts supérieurs de St-Disdier).

Après l'Oligocène, le raccourcissement NE-SW a migré vers l'ouest à travers le Dévoluy, alors que la mise en place de nappes (aujourd'hui préservées en klippes) dans le Dévoluy du SE est antérieure au plissement. Ce plissement à vergence ouest a précédé les 3 km de déplacement sur le Chevauchement Médian du Dévoluy. La quantité de raccourcissement diminue vers le nord, où la compression NE-SW est localement décomposée entre des décrochements dextres N-S et un raccourcissement E-W sur le Chevauchement Médian du Dévoluy, qui se verticalise et se connecte à la faille dextre des Aspres-lès-Corps. Le fait que le Chevauchement Médian du Dévoluy remonte la stratigraphie vers le nord jusqu'à Mt. St-Gicon s'accorde avec une diminution du raccourcissement dans cette direction.

Au toit du Chevauchement Médian du Dévoluy, les calcaires sénoniens, épais dans le Dévoluy du sud, sont brutalement coupés au nord par la zone de failles NE-SW de St-Etienne. A Mt St-Gicon, la réapparition soudaine des calcaires sénoniens dans le toit du Chevauchement Médian du Dévoluy suggère que ce bloc fût un haut paléotectonique dans le bassin. Les caractères stratigraphiques supportent cette hypothèse.

La schistosité trouvée dans le Dévoluy n'est pas spatialement reliée aux plis. Elle est mieux développée dans les Marnes du Queyras, à proximité des failles, où elle apparaît dans une zone de déformation distribuée. Le fait que la schistosité soit approximativement parallèle aux plans axiaux des plis régionaux du Dévoluy traduit la contemporanéité des déformations fragiles et plicatives.

Dans les chaînes subalpines méridionales, le raccourcissement ENE-WSW, d'âge post-Oligocène moyen à Pliocène, diminue vers le Dévoluy où il s'amortit. Le raccourcissement E-W à ESE-WNW de même âge dans les chaînes subalpines septentrionales fut nettement plus important et ne se relie pas à la déformation du Dévoluy. Il y a une discontinuité structurale claire entre les chaînes subalpines du nord et du sud. En conclusion, les Alpes externes occidentales ne forment pas un arc continu mais résultent de deux directions de transport tectonique distinctes, l'une NE-SW à ESE-WNW et l'autre NE-SW à ENE-WSW.

Introduction

Foreland deposits have been used in orogenic belts to bracket the age of deformation and to track tectonic evolution (e.g., Homewood *et al.*, 1986; Schwab, 1986; Tankard, 1986; Burbank and Raynolds, 1988; Jordan *et al.*, 1988; Underschultz and Erdmer, 1991). Throughout the Chaînes Subalpines of the external western Alpine arc, syntectonic Cenozoic deposits are preserved in isolated pockets (Fig. 1a). These deposits, which record the progressive migration of the orogenic load and deformation toward the foreland, have been interpre-

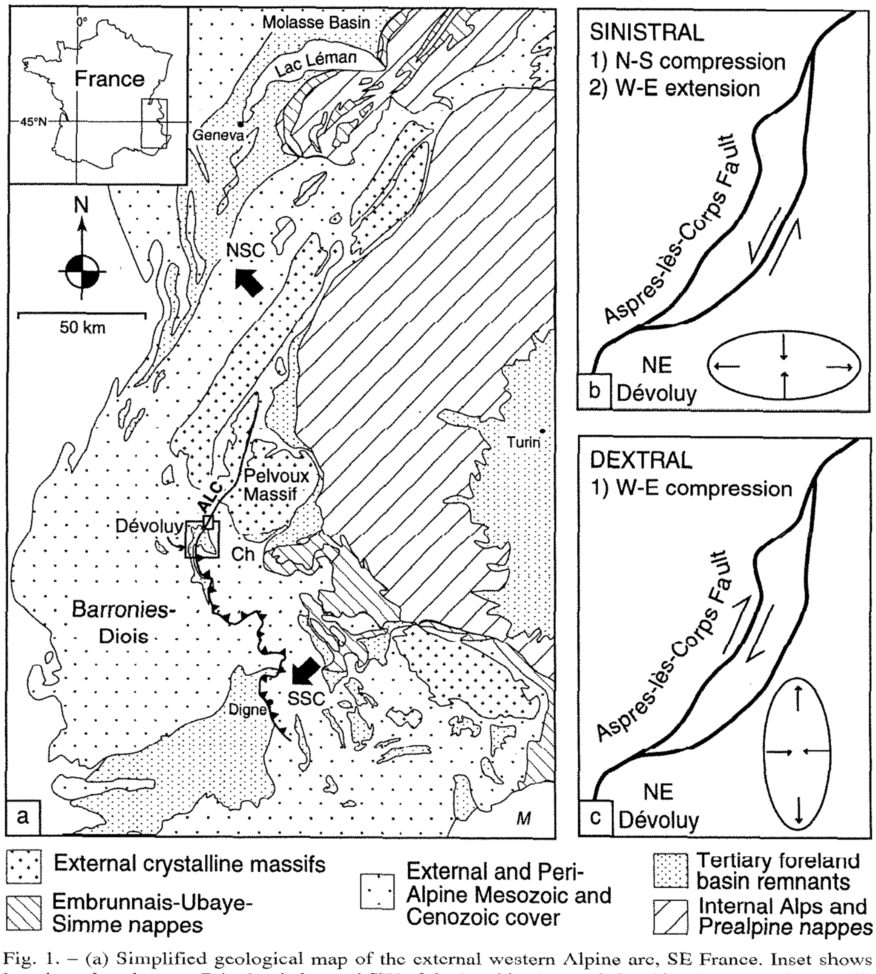

Fig. 1. – (a) Simplified geological map of the external western Alpine arc, SE France. Inset shows location of study area. Dévoluy is located SW of the bend in the arc defined by the external crystalline massifs (large box indicates location of figs. 2, 4; figs. 1b, c shown by small box in NE Dévoluy). Solid arrows show general tectonic transport directions of the northern Chaînes Subalpines (NSC) and the southern Chaînes Subalpines (SSC). ALC: Aspres-lès-Corps Fault; Ch: Champsaur; M: Mediterranean Sea. (b, c) Diagrammatic maps showing kinematics associated with (b) sinistral and (c) dextral movement (Gidon and Pairis, 1976) on the Aspres-lès-Corps Fault.

Fig. 1. – (a) Carte géologique simplifiée de l'arc externe des Alpes occidentales au SE de la France. Le détail montre la localisation de la région étudiée. Le Dévoluy est situé au SW de la courbure de l'arc définie par les massifs cristallins externes (la grande boîte indique la localisation des figures 2 et 4 ; les figures 1b et 1c sont encadrées dans le Dévoluy du NE). Les flèches solides indiquent les directions de transport tectonique général des Chaînes Subalpines du Nord (NSC) et des Chaînes Subalpines du Sud (SSC). ALC : Faille d'Aspres-lès-Corps ; Ch : Champsaur; M : Méditerranée. (b, c) Esquisses montrant la cinématique associée au mouvement (b) senestre et (c) dextre (Gidon et Pairis, 1976) le long de la faille d'Aspres-lès-Corps.

ted as remnants of a single Eocene-Oligocene Alpine foreland basin. Although earlier deformation phases are known (Siddans, 1979; Kerckhove *et al.*, 1980; Ricou and Siddans, 1986; Fry, 1989), the main deformation of the foreland began in the mid-Oligocene (Kerckhove *et al.*, 1980; Pairis *et al.*, 1983, 1984; Pairis and Fabre, 1984; Elliott *et al.*, 1985; Homewood *et al.*, 1985, 1986; Pairis, 1988). Many of the foreland basin remnants were also deformed during the Mio-Pliocene (e.g. Butler, 1985, 1992). The compressional directions around the external arc vary from WNW- and NW-directed in the northern Chaînes Subalpines (e.g. Platt *et al.*, 1989; Butler, 1992) to WSW-directed in the southern Chaînes Subalpines (Siddans, 1979; Platt *et al.*, 1989; Fry, 1989) (Fig. 1a).

This paper documents the late Cretaceous to Mio-Pliocene evolution of the Dévoluy basin, a remnant of the western Alpine foreland basin located southwest of the Pelvoux massif in SE France (Fig. 1a). This basin remnant has been studied because (1) it preserves a fairly complete record of late Mesozoic and Cenozoic sedimentation and tectonism, and (2) it is located at a significant break in the kinematic pattern of the external western Alpine arc. WSW thrusting of the southern Chaînes Subalpines can be traced only as far north as Dévoluy (Fig. 1a; Gidon and Pairis, 1976; Gidon *et al.*, 1980; Fabre *et al.*, 1986) and a tectonic link to the WNW- to NW-directed deformation in northern Chaînes Subalpines has not been established. This implication bears consideration since the geometry and kinematic evolution of the arc are controversial (Graham, 1978; Siddans, 1979; Butler *et al.*, 1986; Ricou and Siddans, 1986; Coward and Dietrich, 1989; Gratier *et al.*, 1989; Platt *et al.*, 1989; Fry, 1989).

From these observations, we document the dynamic evolution of the Dévoluy area and argue that its evolutionary history is comparable to that of time-equivalent Alpine foreland basin remnants. Several unique features are related to prolonged strike-slip movements along the Aspres-lès-Corps Fault, which defines the northern border of the area (Fig. 1a).

Geographical and geological setting

The Dévoluy area is covered by the 1:50,000 geologic maps of Gap (Gidon et al., 1971) and St-Bonnet (Gidon *et al.*, 1980). The N-S oriented Faraud-Grand-Combe and L'Obiou ridges, both composed of Senonian limestones, topographically delimit the Dévoluy valley, which lies at an average elevation of 1200 m above mean sea level (Fig. 2). Approximately 500 m of Tertiary sediments (Figs. 2, 3) are preserved in the valley in the hinge of a N-S trending, W facing periclinal synclinorium (Gidon *et al.*, 1980).

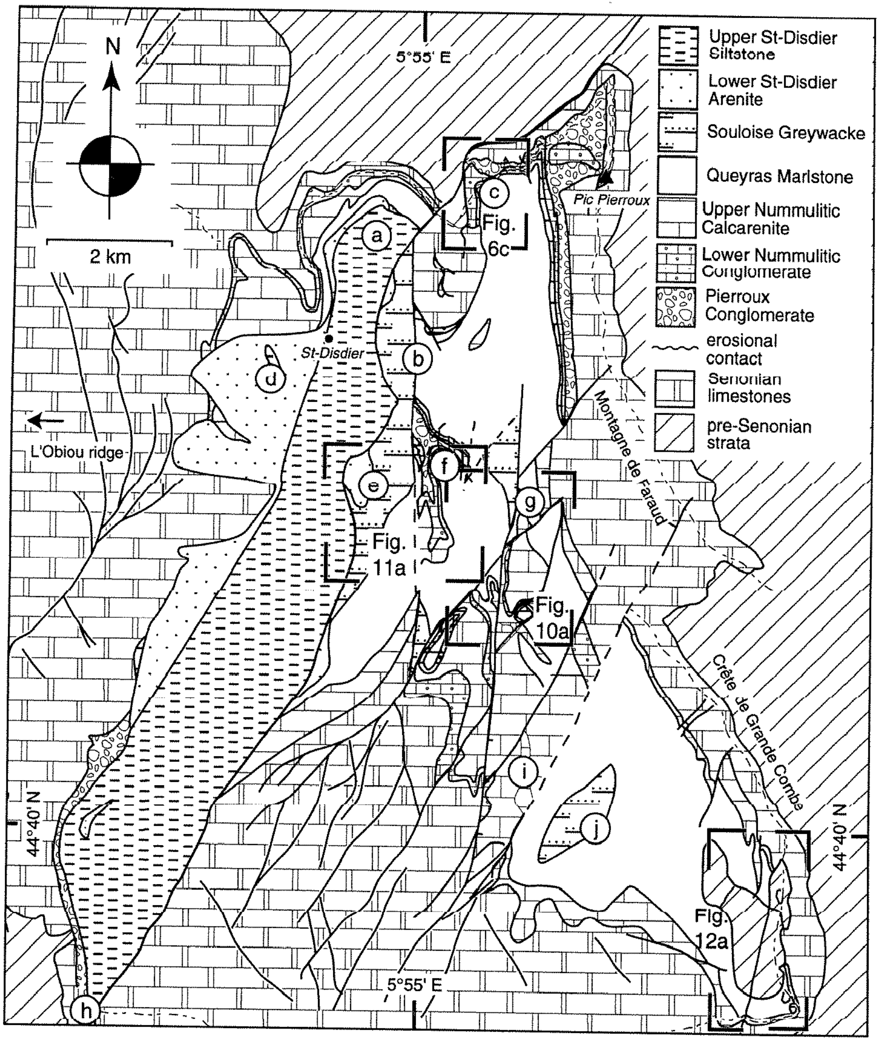

Fig. 2. – Simplified geologic map of Dévoluy. Circled letters indicate general locations of stratigraphic columns shown in fig. 3.

Fig. 2. – Carte géologique simplifiée du Dévoluy. Les cercles entourent les coupes stratigraphiques de la figure 3.

The Tertiary succession records pre-late Eocene continental conditions, followed by late Eocene marine transgression, late Eocene to early Oligocene marine regression, and late Oligocene continental conditions. Dubois (1962), Gidon *et al.* (1980), Pairis *et al.* (1983, 1984a, 1984b), Fabre and Pairis (1984), Fabre *et al.* (1986), Pairis (1988), and Waibel (1990) describe aspects of this succession.

The westward-directed Median Dévoluy Thrust (Fig. 4), which merges northward with the Aspres-lès-Corps Fault (Fig. 4; Gidon and Pairis, 1976; Gidon *et al.*, 1980; Fabre *et al.*, 1986), cuts the Tertiary sediments (Fig. 2). N-S and NE-SW oriented, subvertical faults cut through central Dévoluy (Fig. 4). Klippen of overturned Cretaceous strata overlie Tertiary deposits in the SE (Figs. 2, 4). Most structural research in this area has focused on the complex tectonics of the northern end of the Median Dévoluy Thrust (e.g. Mercier and Neveu, 1956; Glangeaud and d'Albissin, 1958; Gidon and Pairis, 1976), the pre-Senonian folds of the region (Glangeaud and d'Albissin, 1958; Mercier, 1958; Debel-

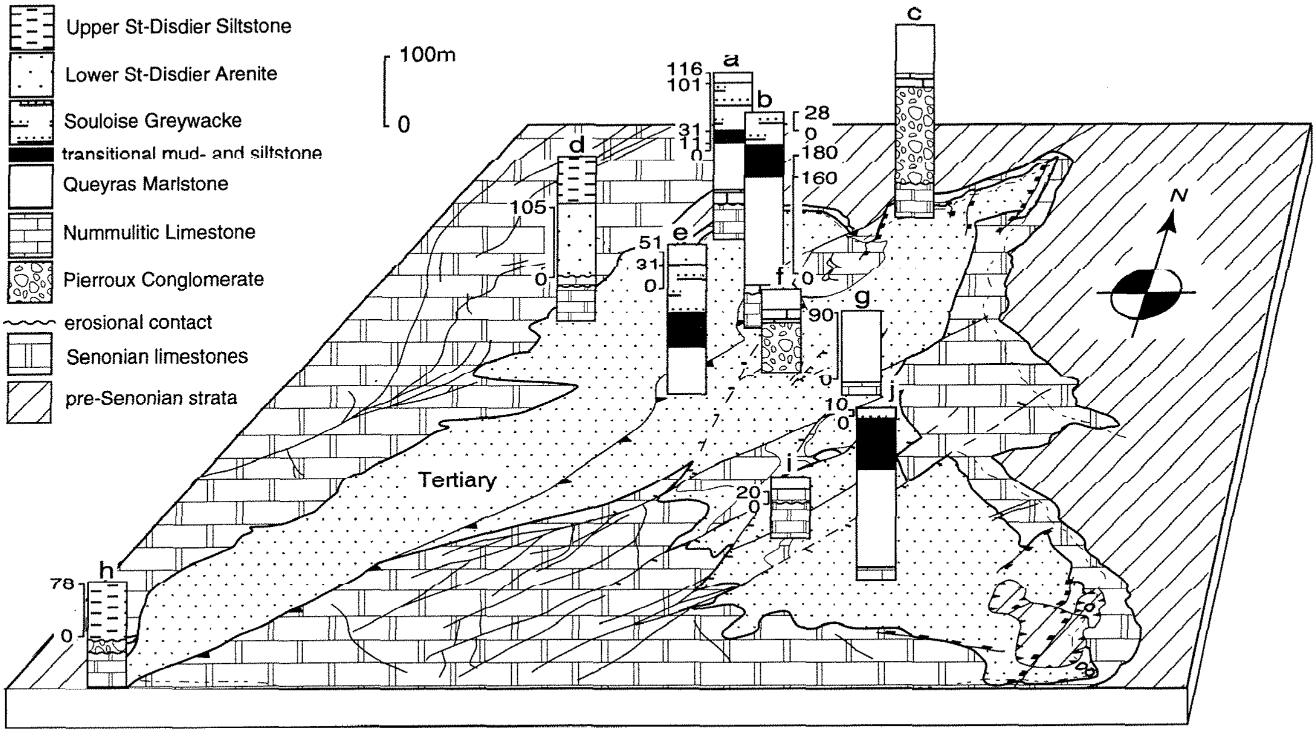

Fig. 3. – Stratigraphic columns, Tertiary sediments, Dévoluy, showing geographic variation in thicknesses of the units on a perspective map. The columns show only those sediments which outcrop in the vicinity of the column. Therefore, upper and lower boundaries are provisional and columns may not show entire sediment column. A scale bar next to the column indicates a thickness measured in the field. Other thicknesses are representative values as determined from field observations and map interpretation. The vertical scale is consistent in space. For clarity, the Nummulitic Limestone is shown as a single unit.

Fig. 3. – Coupes stratigraphiques des sédiments tertiaires du Dévoluy, montrant les variations de l'épaisseur des unités en carte perspective. Les coupes montrent les sédiments affleurant au voisinage de la section mesurée. Les limites inférieures et supérieures sont provisoires et les coupes ne montrent pas nécessairement la section sédimentaire complète. L'échelle près des coupes indique l'épaisseur effectivement mesurée. Les autres épaisseurs sont des valeurs représentatives, déterminées d'après les observations de terrain ou d'après l'interprétation des cartes. L'échelle verticale est constante. Le Calcaire Nummulitique est indiqué comme une seule unité.

Age		Eustatic sea level Haq et al. (1988) high – low	Nomenclature, this study	Gidon et al., 1980	Pairis et al., 1983	Fabre et al., 1986	Pairis, 1988 p. 236	Pairis, 1988 p. 241
Oligocene	Chattian		Upper St-Disdier Siltstone	Grès de St-Disdier	Molasse rouge	Grès de St-Disdier	Molasse rouge	
Oligocene	Rupelian		Lower St-Disdier Arenite		Grès de St-Disdier		Grès de St-Disdier	Formations détritiques terminales gréseuses
			Souloise Greywacke	Marnes à Globigerines	Marnes nummulitiques	Marnes nummulitiques	Flysch de la Souloise	Argillites noires
Eocene	Priab.		Queyras Marlstone	Marno-calcaires priaboniens		Calcaires intermédiaires	Argilites noires/ Marnes à foraminifères/ Marno-calcaires priaboniens	Marnes à foraminifères et Calcaires intermédiaires
			Nummulitic Limestone	Calcaires à Nummulites		Calcaires nummulitiques		
			Pierroux Conglomerate	Poudingues et formations continentales de la base du Tertiare	Conglomérats/couches infranummulitiques			

Table I. – Comparison of the stratigraphic nomenclature used in this study with previously published nomenclature. Eustatic sea level curve modified after Haq *et al.* (1988).

Tabl. I. – Comparaison de la nomenclature stratigraphique utilisée dans cette étude avec la nomenclature publiée auparavant. Courbes eustatiques du niveau de la mer d'après Haq et al. (1988).

mas and Lemoine, 1970; Gidon *et al.*, 1970; Arnaud, 1974; Odonne and Vialon, 1987) and the role of the Aspres-lès-Corps Fault in the early evolution of the area (Gidon and Pairis, 1976; Gidon, 1979).

Local stratigraphical nomenclature

Field mapping at the 1:10,000 scale allowed six Tertiary stratigraphic units to be distinguished. These are the Pierroux Conglomerate, the Nummulitic Limestone, the Queyras Marlstone, the Souloise Greywacke, the Lower St-Disdier Arenite, and the Upper St-Disdier Siltstone (Table I; Figs. 2, 3). This new informal nomenclature is proposed because much of the currently existing nomenclature in Dévoluy is either contradictory to Alpine nomenclature established elsewhere, or is internally inconsistent (Table I). A formal sedimentological and stratigraphic analysis of the formations is the subject of a paper in preparation. Important sedimentary characteristics of the units are presented below, but detailed documentation is beyond the scope of this paper.

Basin Evolution

Pre-Priabonian structures and sedimentation

Early Alpine structures across the Alpine foreland of SE France are divided into two phases based on stratigraphic

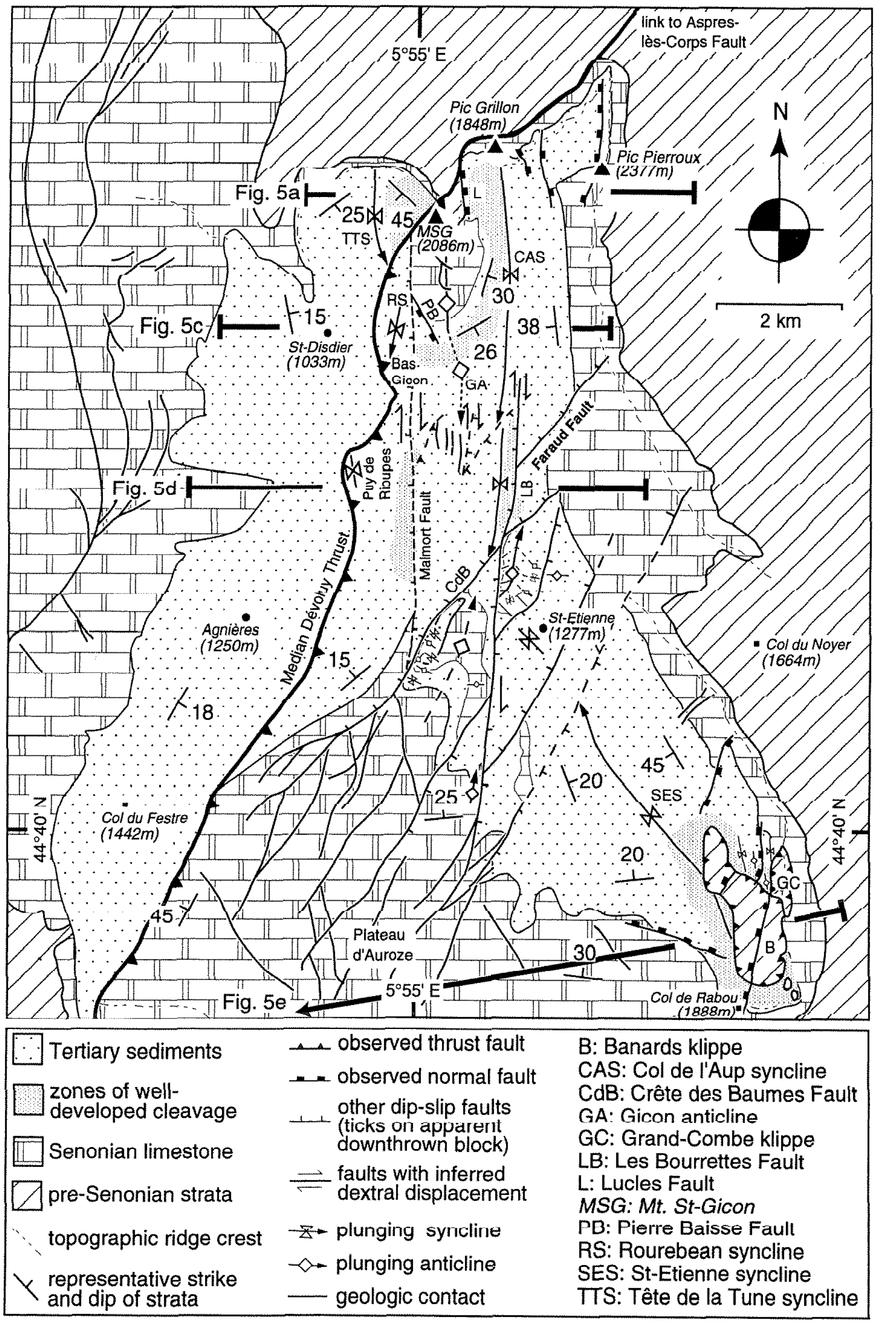

Fig. 4. – Structural map of Dévoluy. Modified in part after Gidon *et al.* (1980).

Fig. 4. – Carte structurale du Dévoluy. Modifiée partiellement d'après Gidon et al. *(1980).*

relationships: the pre-Senonian phase of Turonian (Siddans, 1979; Debrand-Passard *et al.*, 1984) to late Coniacian (Arnaud, 1974) age, and a phase that is contemporaneous with Eocene folding in Provence (Flandrin, 1966). There is evidence of both phases in Dévoluy, especially in the northeast, where the Aspres-lès-Corps Fault (Fig. 1a) may have been active since at least the middle Cretaceous (Tricart, 1984).

Pre-Priabonian folding

In Dévoluy, upper Cretaceous marine limestones lie above locally strongly folded Albian-Cenomanian and older strata. This complex unconformity constrains the age of pre-Senonian folding as early Turonian to Coniacian (Mercier, 1958; Gidon *et al.*, 1980). Structural data published on these early folds describe isolated W-E to NE-SW trending folds in northern, southwestern, and eastern Dévoluy (Glangeaud and d'Albissin, 1958; Debelmas and Lemoine, 1970; Gidon *et al.*, 1970; Arnaud, 1974; Odonne and Vialon, 1987). A NE-SW trending, NW-facing, tight to isoclinal, recumbent fold train is visible on the external northeastern wall of the Dévoluy valley (Huyghe and Mugnier, 1995, their fig. 6). These folds have long normal limbs and short overturned limbs that are locally thrust out. The pre-Senonian deformation in Dévoluy has been linked to N-S compression (Baudrimont and Dubois, 1977; Siddans, 1979). The folds are locally overprinted by later Alpine folding (Odonne and Vialon, 1987).

The sediments above the unconformity are approximately 500-700 m thick. They are predominantly upper Senonian (Campanian-Maastrichtian). The lower part of the section is composed of sandy limestones and cherty limestones which contain planktonic foraminifera (globotruncanids), belemnites, and ammonites (Gidon *et al.*, 1980). These sediments are overlain by bioclastic limestones containing bivalves (*Pycnodonta vesicularis*) and benthic foraminifera (*Orbitoides media, Siderolites*) (Gidon *et al.*, 1980). Continental limestone conglomerates at the top of the section contain *Microcodium* (Gidon *et al.*, 1980). Silcrete layers with mudcracks are interbedded with the conglomerates, indicating subaerial exposure (Gidon *et al.*, 1980). Thus, the sediments reflect a relatively rapid upsection shallowing (Gidon *et al.*, 1980).

The Eocene phase of folding (referred to as "post-Senonian" by Glangeaud and d'Albissin, 1958 and "pre-Nummulitic" by Gidon *et al.*, 1980) affected Senonian and older rocks. In northern Dévoluy, folds are approximately NNW-SSE trending and W-facing, and have steeply-dipping to overturned limbs (x and y, Fig. 5a; x' and y', Fig. 5b). The folds are less well-developed elsewhere in Dévoluy. In central Dévoluy, Senonian strata are gently folded such that there is an angular unconformity of 10-20° with the overlying Tertiary strata. Further south, the angular unconformity is typically less than 10°. This second phase of folding predated deposition of the Pierroux Conglomerate, which overlies the eroded folds (Figs. 5a, b). However, since the age of the Pierroux Conglomerate is uncertain (see below), the age of the second phase of folding can be no better constrained than pre-mid Bartonian and post-late Maastrichtian.

Paleocene to Priabonian faulting

Local uplift and extensional faulting occurred in northeastern Dévoluy before and during deposition of the Priabonian Nummulitic Limestone (Gidon and Pairis, 1976; Fabre *et al.*, 1985). The features reflecting this tectonism are the Median Dévoluy Thrust, which had a pre-Priabonian downthrow to the east before being inverted in the Mio-Pliocene (Gidon and Pairis, 1976), the down-to-the-east Lucles Fault east of Mt. St-Gicon, the Pic Grillon growth structure northeast of Mt. St-Gicon, and the down-to-the-southwest Pierre Baisse Fault southwest of Mt. St-Gicon. All of the structures occur immediately south of the Aspres-lès-Corps Fault in the vicinity of Mt. St-Gicon (Fig. 4).

Several lines of evidence point to down-to-the-east, extensional displacement on the Median Dévoluy Thrust during the Eocene (Gidon and Pairis, 1976). (1) There is extensional offset preserved in the Jurassic and Cretaceous sediments north of Mt. St-Gicon (Fig. 2; also see Gidon and Pairis, 1976, their Fig. 3). (2) In northern Dévoluy, the Senonian limestones are 150 m thicker in the hanging-wall of the fault than in the foot-wall (Fig. 5b; also see Gidon and Pairis, 1976, their Fig. 4a). (3) In southern Dévoluy, the Senonian limestones are locally completely eroded in the foot-wall (e.g., 1 km north of h, Fig. 2), but are several hundred meters thick in the hanging-wall. (4) The early Tertiary Pierroux Conglomerate is a carbonate-rich conglomerate up to 150 m thick in the hanging-wall, but is a thin, medium-grained quartzarenite with carbonate cement or is absent in the foot-

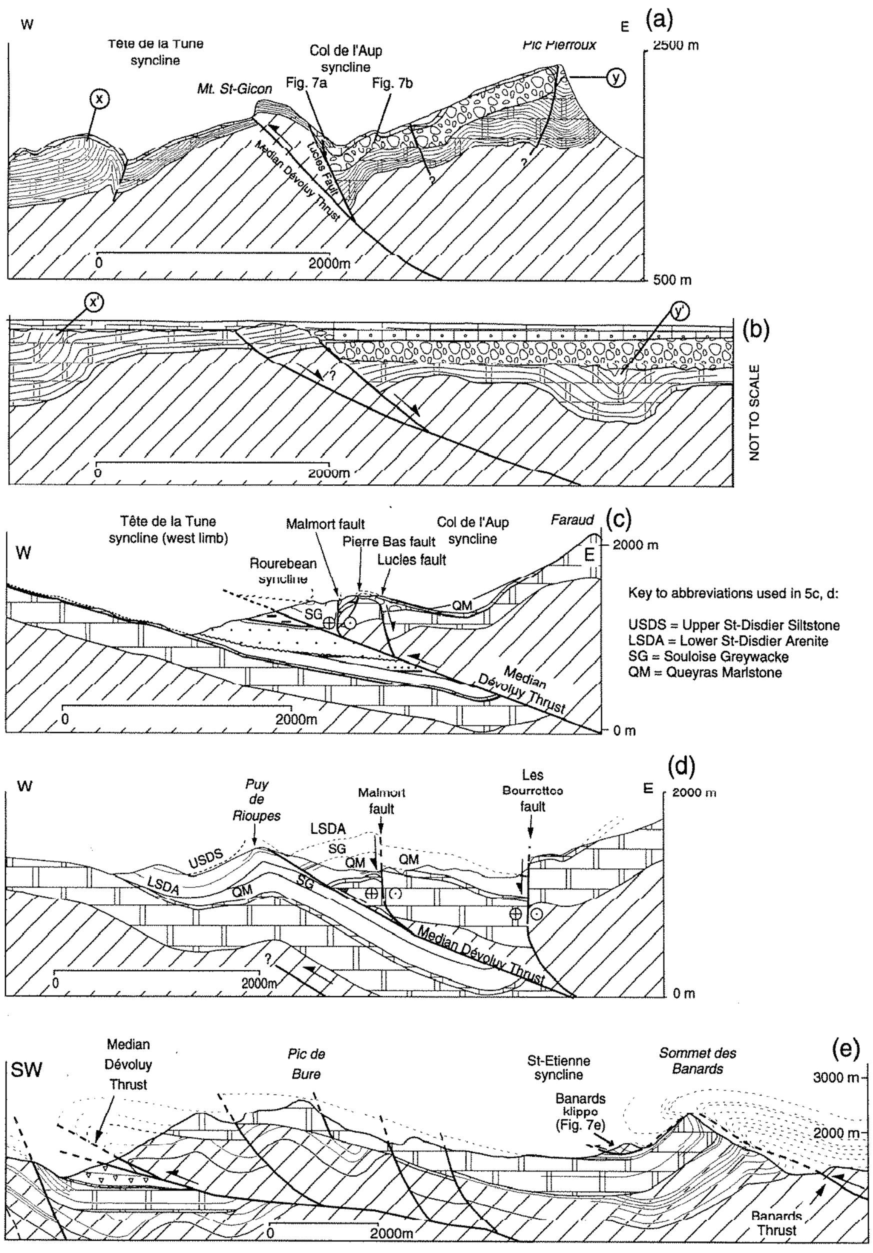

Fig. 5. – Cross sections (located in fig. 4). Symbols in 5a, c-e as in fig. 3, except inverted triangles (Fig. 5e), which are post-late Oligocene "Nagelfluh" south of the study area. Symbols in 5b as in fig. 2. (a) Profile through northern Dévoluy; x and y show observed marked angular unconformities between the Senonian and Tertiary which constrain the locations of Eocene folds. (b) Restoration of fig. 5a to top Nummulitic Limestone; x' and y' show restored positions of x and y from fig. 5a. Note the high degree of erosion of anticlines of the Senonian limestone. Displacement on the Median Dévoluy Thrust is 500 m; estimated post-Oligocene shortening is 10 %. Thicknesses of the Tertiary sediments exaggerated to show thickening of Pierroux Conglomerates away from the Lucles Fault, thinning of Nummulitic Limestone away from the Lucles Fault, and onlap relationship of Nummulitic Limestone lithofacies on paleotopography of Mt. St-Gicon. (c) Profile through north-central Dévoluy. Displacement on the Median Dévoluy Thrust is approximately 2 km; overall shortening is 40%. (d) Profile across central Dévoluy showing down-to-the-east downthrow on the dextral Malmort and Les Bourrettes Faults. (e) Profile through southwestern Dévoluy, showing Banards Klippe rotated on the east limb of the St-Etienne Syncline.

Fig. 5. – Coupes structurales (localisées figure 4). Les symboles de 5a, c-e sont identiques à ceux de la figure 3, à l'exception des triangles inversés (figure 5e), indiquant la "Nagelfluh" au sud du Dévoluy. Les symboles de 5b sont identiques à ceux de la figure 2. (a) Profil à travers le Dévoluy du nord ; x et y montrent les discordances angulaires entre le Sénonien et le Tertiaire qui documentent les plis éocènes. (b) Reconstruction palinspastique de la coupe 5a au niveau du Calcaire Nummulitique ; x'et y'montrent les positions reconstituées de x et y de la coupe 5a. Remarquer l'érosion importante des anticlinaux des calcaires sénoniens. Le déplacement sur le chevauchement médian du Dévoluy est de 500 m ; le raccoursissement post-oligocène est estimé à 10 %. L'épaisseur des sédiments tertiaires est exagérée pour montrer l'augmentation d'épaisseur des Conglomérats de Pierroux et l'amincissement du Calcaire Nummulitique à l'E de la faille normale de Lucles, ainsi que la position transgressive des Calcaires Nummulitiques dans la paléogéographie du Mt. St-Gicon. (c) Coupe à travers le Dévoluy nord-central. Le déplacement sur le chevauchement médian du Dévoluy est d'environ 2 km ; le raccoursissement général de 40 %. (d) Coupe à travers le Dévoluy central montrant l'abaissement à l'est des Failles dextres de Malmort et des Bourrettes. (e) Coupe à travers le Dévoluy sud-occidental, montrant la Klippe des Banards sur le flanc oriental du Synclinal de St-Etienne.

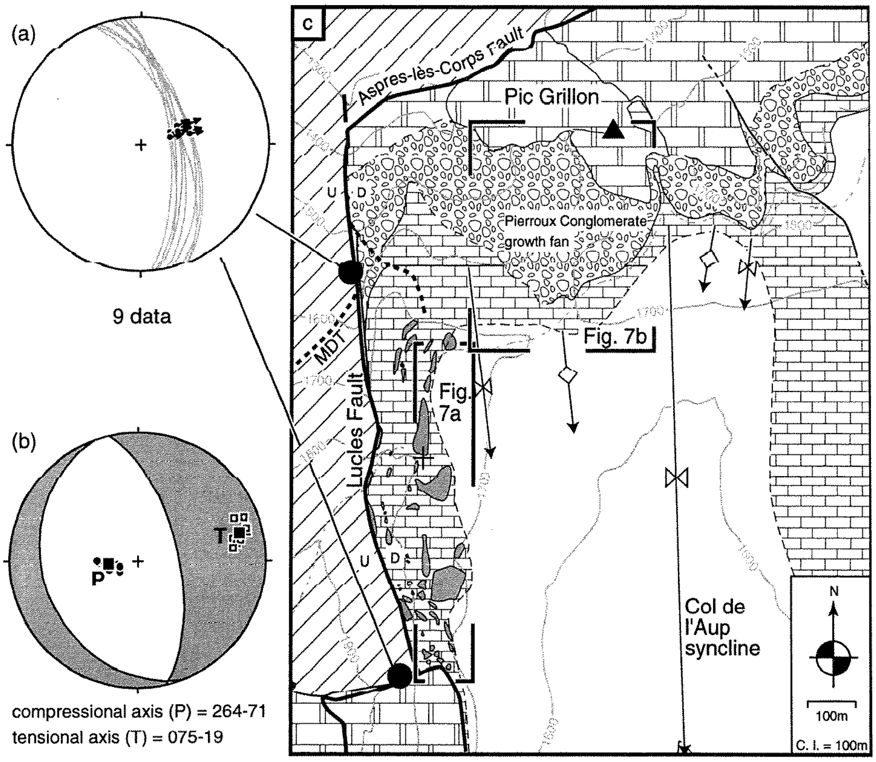

Fig. 6. – (a) Equal area, lower hemisphere stereonets of Lucles Fault data. Locations of measurements indicated in fig. 6c. Great circles are measured orientations of the fault plane. Arrows show movement of the hanging-wall relative to the foot-wall, as measured on grooves. (b) Fault plane solution (linked Bingham axes) for the Lucles Fault. (c) Detailed map (located in fig. 2) of Pic Grillon area. MDT = Median Dévoluy Thrust. Symbols as in fig. 3, except grey shaded blocks, which are Senonian olistoliths in the Nummulitic Limestone (see also figs. 7a, f).

Fig. 6. – (a) Stéréogrammes (canevas de Schmidt, hémisphère inférieur) des données structurales de la faille de Lucles. Les stations de mesures sont localisées dans la figure 6c. Les grands cercles représentent le plan de faille. Les flèches montrent le mouvement relatif du toit par rapport au mur, mesuré sur des stries. (b) Solution cinématique (axes de Bingham assemblés) du jeu de faille de Lucles. (c) Carte détaillée (localisée figure 2) des environs du Pic Grillon. MDT = Chevauchement Médian du Dévoluy. Les symboles sont identiques à ceux de la figure 3, à l'exception des blocs pointillés qui représentent des olistolites sénoniens dans les Calcaires Nummulitiques (cf. figures 7a, 7f).

wall (Fig. 3). (5) The thickness of the Nummulitic Limestone does not vary significantly across the fault (Figs. 5a, c, d). These observations indicate that extensional movement on the Median Dévoluy Thrust postdated deposition of the Senonian limestones and predated deposition of the Nummulitic Limestone.

The second extensional feature, the Lucles Fault (Gidon and Pairis, 1976), has an average strike and dip of 169-64E (Fig. 6a)(1). Down-dip grooves several centimeters deep and up to 1 m long on the fault plane give a kinematic solution(2) which indicates that the tensional axis ($\sigma3$) was oriented 075-19° (Fig. 6b). Senonian strata are displaced downdip by at least 500 m at the northern end of the fault (Figs. 5a, 5b). The offset may have been more if the fault was later partially inverted (Gidon and Pairis, 1976). The offset decreases to the south and the fault tips out south of Mt. St-Gicon (Gidon and Pairis, 1976). In the footwall of the fault, the Nummulitic Limestone onlaps the paleogeographic high of Mt. St-Gicon (Fig. 5b). In the hangingwall, the Pierroux Conglomerate and Nummulitic Limestone contain abundant Senonian debris, most notably Senonian blocks within the Nummulitic Limestone that can reach up to 50 m in length (Figs. 6c, 7a, 7f; Gidon and Pairis, 1976; Fabre *et al.*, 1985). These two factors indicate that the foot-wall block was a topographic feature during deposition of the Nummulitic Limestone that was actively eroded in the Priabonian. Moreover, the Nummulitic Limestone thins stratigraphically away from the Lucles Fault (Fig. 5b; Fabre *et al.*, 1985), which indicates that the fault was active during the deposition of the Nummulitic Limestone.

The third feature that records Eocene tectonic activity is the Pic Grillon growth structure. Pic Grillon is a pillar-like Senonian block with a 60°S dipping southern face. Beds of the Pierroux Conglomerate thicken away from the southern face in a cumulative wedge (Figs. 7b, g; Gidon and Pairis, 1976, their fig. 7). The angle of onlap of the beds steepens progressively downsection. This rotative onlap indicates Pic Grillon was an actively uplifting topographic feature during deposition of the Pierroux Conglomerate. The Lower Nummulitic Conglomerate onlaps Pic Grillon and does not show evidence of having been affected by syndepositional uplift (Fig. 7g, inset). Therefore, the uplift is considered to have ceased by the Priabonian.

The Pierre Baisse Fault (Fig. 4; Gidon and Pairis, 1976) trends NW-SE and dips steeply to the SW. It crops out for approximately 500 m along the SW corner of Mt. St-Gicon. At its northwestern extremity, the fault carries the Lower Nummulitic Conglomerate and Upper Nummulitic Calcarenite in its hanging wall. Along strike to the southwest, a second, stratigraphically higher bed of nummulitic conglomerate seals the fault and is deposited over the Upper Nummulitic Calcarenite in the hangingwall. This repetition of the nummulitic conglomerates indicates that the fault was active syndepositionally (Gidon and Pairis, 1976, their fig. 6). Further to the southeast, the fault is laterally continuous with a series of syndepositional microfaults (Gidon and Pairis, 1976, their fig. 5).

In summary, numerous observations in northeastern Dévoluy indicate enhanced tectonic activity in that area before and during the Priabonian. The proximity of these tectonic features to the Aspres-lès-Corps Fault (Figs. 1, 4) and the relative lack of similar tectonic features to the south strongly suggest that they were generated by activity on the Aspres-lès-Corps Fault. Early movement on this fault was sinistral on its eastern branch and dextral on its western branch

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(1) All fault and fold data presented in this paper were plotted and analyzed using the Macintosh computer program Stereonet, version 4.9.5, written by R. W. Allmendinger (1988-1995).

(2) All kinemtic analyses were performed using the Macintosh computer program FaultKin, version 3.25, written by R. W. Allmendinger, R. A. Marrett, and T. Cladhous (1989-1992).

(Figs. 1b, 1c; Gidon and Pairis, 1976). The N-S oriented compression of the pre-Senonian folds (Tricart, 1984) and the W-E extension along the normal faults are consistent with the sinistral movement (Fig. 1b), while the appproximately W-E compression recorded in the post-Senonian folds is consistent with the dextral movement (Fig 1c). Such a scenario implies that early movement on the Aspres-lès-Corps Fault alternated episodically between sinistral and dextral. Early uplift of the Pelvoux Massif to the east (Ford, 1996) may have been associated with this activity. An alternate explanation for the late extension is that it reflects tensional response of the lithosphere to loading in more internal Alpine domains (P. Tricart, pers. comm.).

The Pierroux Conglomerate

The age of the Pierroux Conglomerate is poorly constrained because the formation does not contain fossils. Stratigraphically, the formation rests unconformably on folded middle and Upper Cretaceous sediments, the youngest of which are Upper Maastrichtian. It is overlain by the Priabonian Nummulitic Limestone except in southwestern Dévoluy, where it is unconformably overlain by the Upper St-Disdier Siltstone (Figs. 2, 3). Therefore, its age is constrained as post-late Maastrichtian and pre-Priabonian. Gidon *et al.* (1980) allocate it to the "Eocene (Priabonian-Lutetian?)", while Pairis *et al.* (1983, 1984a) give its age as mid-Bartonian to mid-Priabonian.

The Pierroux Conglomerate is variably present throughout the basin (Figs. 2, 3). It is a clast-supported conglomerate 30-150 m thick in outcrops east of the Median Dévoluy Thrust. West of the Median Dévoluy Thrust, a 10 m thick quartzarenite occurs in an analogous stratigraphic position in one outcrop in southwestern Dévoluy (Fig. 3, column h; Gidon *et al.*, 1980). The Pierroux Conglomerate is stratigraphically missing in NW and SE Dévoluy. The formation is thickest in northeastern Dévoluy, and thins to the south and west (Fig. 3). Similarly, clast size decreases from an average of 50 cm in the northeast to medium- to coarse-grained sand in the southwest.

The formation is dominated by 1-5 m thick, crudely bedded, clast-supported conglomerate beds, which are lenticular to tabular and have erosional bases and conformable or eroded tops. The beds are composed of poorly sorted, poorly to moderately rounded, locally-sourced Senonian clasts and a moderately sorted, medium- to coarse-grained calcarenite matrix. They are occasionally interbedded with calcareous siltstones and fine- to medium-grained calcarenite beds which are discontinuous over 10s of meters. Many of the beds have a distinctive red color. In southwestern Dévoluy, the only lithofacies present is a medium- to coarse-grained, well-sorted quartzarenite with carbonate cement (Gidon *et al.*, 1980). The age and geometric relationship of this lithofacies to the conglomeratic lithofacies east of the Median Dévoluy Thrust is not known.

The formation was deposited in a continental setting (Gidon *et al.*, 1980), probably in an alluvial fan system (e.g., Nilsen, 1982) associated with early pre-Priabonian extensional faults. Formation thickness and grain size trends indicate that the depocenter of the fan system was in the northeast.

Priabonian deposition

Sedimentation during the Priabonian was carbonate- to marl-dominated. The Nummulitic Limestone and the Queyras Marlstone were deposited during this time.

The Nummulitic Limestone

The Nummulitic Limestone is dated as Priabonian based on foraminiferal assemblages (Dubois, 1962; Gidon *et al.*, 1980; Pairis *et al.*, 1983, 1984a; Fabre and Pairis, 1984; Fabre *et al.*, 1986; Pairis, 1988). The formation overlies either the Senonian limestone or the Pierroux Conglomerate. It is conformably overlain by the Queyras Marlstone. The formation consists of two members, the Lower Nummulitic Conglomerate and the Upper Nummulitic Calcarenite.

The Lower Nummulitic Conglomerate is present everywhere in the basin except southeastern and southwestern Dévoluy (Figs. 2, 3). The lower boundary of the member varies according to the substratum. Above the Pierroux Conglomerate, the lower boundary is characterized by a shift from clast-supported to matrix-supported texture. The transition is also documented by the appearance of *Nummulites* in the matrix of the Lower Nummulitic Conglomerate and an increase in the rounding of the clasts. Above the Senonian limestones, the lower surface is irregular and erosive.

The Lower Nummulitic Conglomerate is usually 1-10 m thick. However, northeast of Mt. St-Gicon, in the hanging wall of the Lucles Fault, it is 100 m thick and contains numerous large Senonian limestone blocks (Figs. 6c, 7a, 7f). The unusual thickness and the presence of the Senonian blocks is the result of syndepositional activity on the Lucles Fault (Gidon and Pairis, 1976).

The Lower Nummulitic Conglomerate consists of two characteristic lithofacies. The first lithofacies is a non-conglomeratic, well-sorted, medium-grained calcarenite (packstone-grainstone of Dunham, 1962). It occurs in beds 1-100 cm thick. The second lithofacies is more diagnostic. It is most often a bimodally sorted, matrix- to clast-supported conglomerate that consists of well-rounded to subangular Senonian limestone and chert clasts and a well-sorted, well-rounded, medium-grained calcarenitic matrix with some interstitial micrite. This lithofacies occurs in layers up to 300 cm thick which display low-angle planar bedding. Intercalated microconglomerates occur in thin streaks. The two major lithofacies are regularly interbedded. Both lithofacies contain abundant marine fossils and fragments, including *Nummulites*, red algae, and *Dasycladaceae*. The above characteristics are consistent with a shallow marine environment with variable energy, such as the upper shoreface, the foreshore, or on the flanks of shallow tidal bars (McCubbin, 1982; Inden and Moore, 1983).

The Upper Nummulitic Calcarenite is present throughout the basin. It is transitional with the Lower Nummulitic Conglomerate below it and the Queyras Marlstone above it. The lower boundary is taken at the upper surface of the last conglomerate bed. The upper boundary is taken at the top of the last bed contai-

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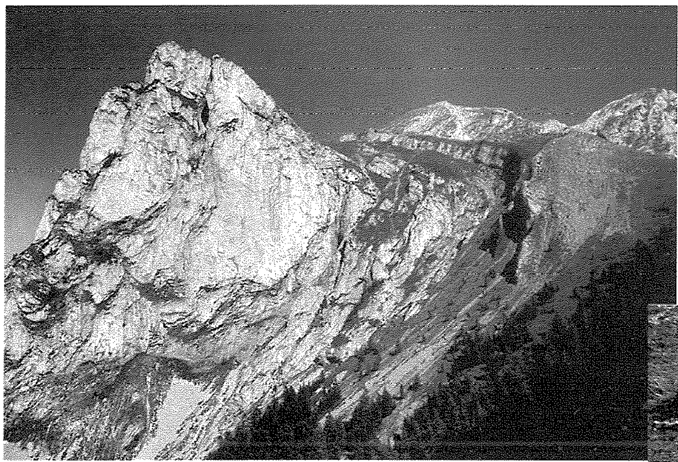

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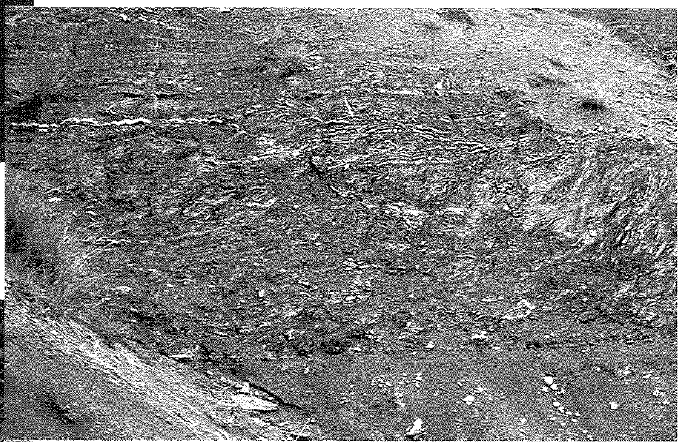

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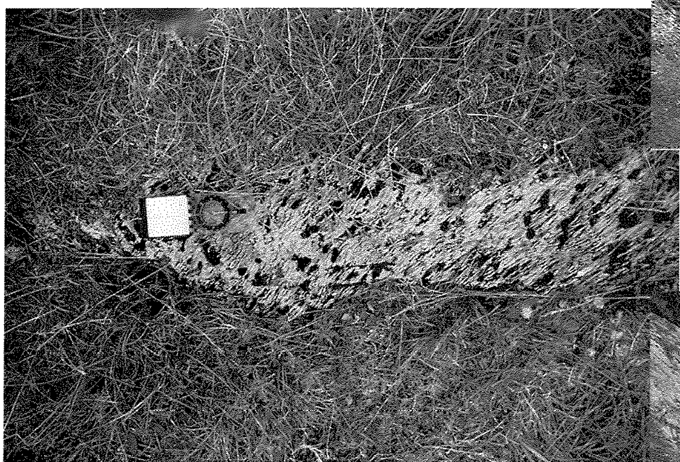

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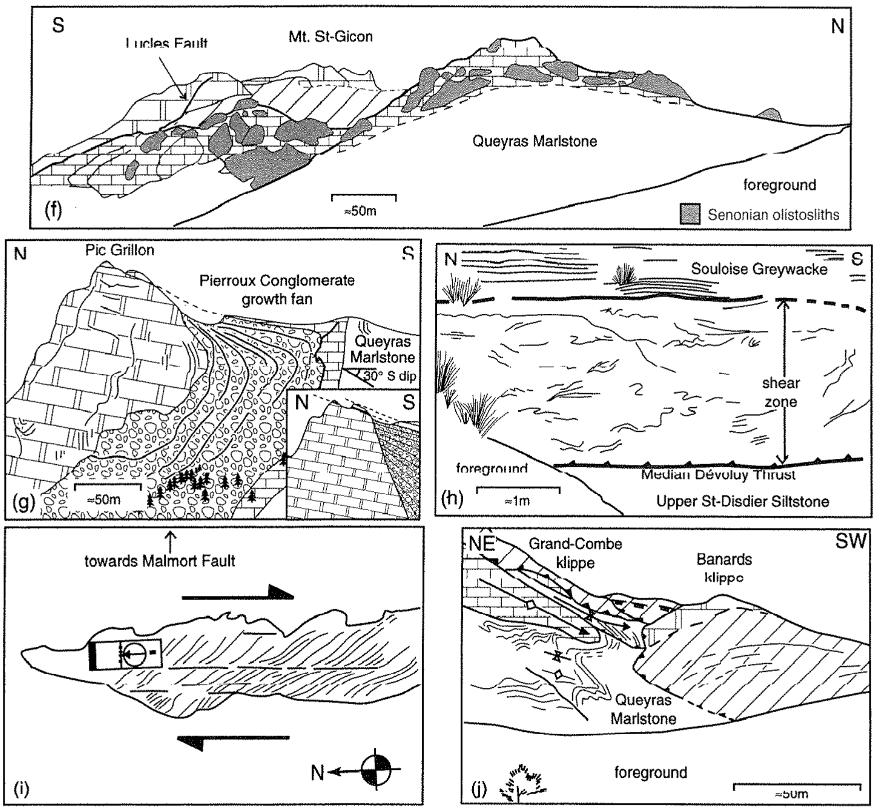

Fig. 7. – (a-e) Field photographs. Compare to figs. 7f-j. (a) Senonian olistoliths (light) in the Nummulitic Limestone (dark) in the hanging wall of the Lucles Fault. Location: figs. 5a, 6c. (b) The Pic Grillon growth fan in the Pierroux Conglomerate. The apparent overturning of beds of the Pierroux Conglomerate is a three-dimensional cutting effect, and does not actually occur. Beds dip to the south in reality (see inset, fig. 7g). Location: figs. 5a, 6c. (c) The Median Dévoluy Fault as exposed at Bas Gicon. Location: BG, fig. 4. (d) Shear bands associated with the Malmort Fault. Compass for scale. Location: fig. 11a, inset (b). (e) Banards and Grand-Combe Klippen. Location: figs. 5e, 12a. (f-j) Line drawings of figs. 7a-f. Where used, patterns as in fig. 3. The inset in fig. 7g (modified after Gidon and Pairis, 1976) shows the schematic relationship of the units at Pic Grillon.

Fig. 7. – (a-e) Photographies de terrain. Comparez avec les figures 7f-j. (a) Olistolites sénoniens (clairs) dans des Calcaires Nummulitiques (foncés) dans le toit de la faille normale de Lucles. Localisation: figures 5a et 6c. (b) Le cône alluvial syntectonique du Pic Grillon dans le Conglomérat de Pierroux. L'inversion apparente de pendage des couches du Conglomérat de Pierroux est un effet tri dimensionnel de la coupe, et n'existe pas en réalité. Le vrai pendage des couches est vers le sud (cf. cartouche, fig. 7g). Localisation : figures 5a et 6c. (c) Le Chevauchement Médian du Dévoluy à Bas Gicon. Localisation: BG, figure 4. (d) Bandes de cisaillement associées à la Faille de Malmort. La boussole donne l'échelle. Localisation : localité (b), figure 11a. (e) Les Klippes des Banards et de la Grand-Combe. Localisation: figures 5e, 12a. (f-j) Esquisses des figures 7a-f. En partie, mêmes symboles qu'en figure 3. La relation schématique des formations au Pic Grillon est indiquée en cartouche de la figure 7g (modifiée d'après Gidon et Pairis, 1976).

ning visible *Nummulites* in hand specimen. The member is 1-15 m thick.

The Upper Nummulitic Calcarenite has one predominant lithofacies. It is a moderately-sorted, well-bedded calcilutite to calcarenite with well-rounded to subangular grains (wackestone through packstone of Dunham, 1962). This lithofacies is occasionally interbedded with a second, finer-grained lime mudstone to wackestone lithofacies. Beds of the first lithofacies are 10-75 cm thick. They typically have irregular to undular upper and lower surfaces and are internally structureless. Beds of the second lithofacies are less than 1 cm thick. The median grain size of the Upper Nummulitic Calcarenite decreases upsection from medium-grained to fine-grained calcareous sand. The member is characterized by a general lack of coarse-grained Senonian clasts and a decrease in the diversity of marine fossils. It is interpreted to have been deposited in a medium-energy ramp-type shelf environment (Wilson and Jordan, 1983; Tucker and Wright, 1988).

Overall, the Nummulitic Limestone records deepening-up shallow marine conditions.

The Queyras Marlstone

The Queyras Marlstone is dated as late Priabonian (planktonic biochronozone P16-17, nannofossil biochronozone NP 19-20) by Gidon *et al.* (1980), Pairis *et al.* (1983, 1984a), Fabre *et al.* (1986), and Pairis (1988) based on planktonic and benthic foraminifera and on nannofossil assemblages.

It is predominantly present in the hanging-wall of the Median Dévoluy Thrust, but is also present in its foot-wall in northern Dévoluy (Fig. 2). It is 125 m thick in one complete section in north central Dévoluy (Fig. 3). Elsewhere, it is incompletely exposed, so lateral variations in thickness can only be estimated. The lower boundary of this unit is everywhere gradational with the Upper Nummulitic Calcarenite. The unit grades upsection into the Souloise Greywacke through a 25-50 m thick, black mud- to siltstone (Fig. 3). This upper transitional lithofacies contains carbonaceous material and is characterized by its black color, fine grain size, and extremely thin bedding. The upper surface of the Queyras Marlstone is provisionally taken at the top of the transitional lithofacies.

The Queyras Marlstone contains three characteristic lithofacies. The first lithofacies occurs as 1-5 m thick, thinly bedded, fine- to coarse-grained, tabular marlstone beds with a wackestone to packstone texture. The second lithofacies occurs in structureless, very fine-grained, tabular marlstone and fine calcarenite (mudstone to wackestone) beds 1-5 m thick. These first two lithofacies are repetitively interbedded. Both lithofacies show a high degree of bioturbation by *Zoophycos*, *Chondrites*, *Planolites*, and Skolithos ichnofauna (*Zoophycos* ichnolithofacies). Additionally, these lithofacies contain abundant planktonic foraminifera. They have variable amounts of siliciclastic debris. The third lithofacies occurs in 1-75 cm thick, internally structureless, coarse- to fine-grained, fining-up carbonate-rich sandstone beds with sharp bases and occasional sole marks or imbricated clasts. The lithic grains are monocrystalline quartz with straight and undulose extinction, carbonate lithic fragments, and occasional feldspars.

The *Zoophycos* ichnolithofacies suggests bathyal conditions with reduced oxygen and a high organic content in the sediment (Seilacher, 1978). Therefore, the Queyras Marlstone is interpreted as having been deposited on a low energy, deeper shelf to shallow slope environment. The graded sandstones towards the top of the unit are interpreted as turbidites. Based on these interpretations, the presence of the shallow water coccolith species *Lanternithus minutus* noted by Fabre *et al.* (1986) is possibly the result of redeposition in a turbidite, and not of shallow paleobathymetric conditions, as interpreted by these authors. The transitional lithofacies at the top of the unit is indicative of increased terrigenous influx. Similar influxes on slopes have been related to tectonic uplift and erosion or to climate change. An alternative explanation is that there was an autocyclic shifting of depositional systems (H. Sinclair, pers. comm.).

Latest Priabonian and Oligocene deposition

Siliciclastic deposition dominated the latest Priabonian through the Oligocene. The Souloise Greywacke, the Lower St-Disdier Arenite, and the Upper St-Disdier Siltstone were deposited during this time.

The Souloise Greywacke

The Souloise Greywacke is dated as Upper Eocene to Lower Oligocene based on foraminifera (Gidon *et al.*, 1980). It crops out primarily in northern Dévoluy, although it is also present in central and southeastern Dévoluy (Fig. 2). It is 100 m thick in the only complete section, in northern Dévoluy (Fig. 3). The lateral variability in thickness is not known. The lower boundary of the unit is transitional with the Queyras Marlstone. The abrupt upper boundary is defined at the top of the last mud- to siltstone bed below the overlying thicker, coarser grained sandstone beds of the Lower St-Disdier Arenite.

The unit is characterized by a lithofacies association which occurs in repetitive, 1 to 80 cm thick beds which fine-up from medium- to very fine-grained sand at their bases to silt- and mudstone at their tops. The bases of the graded intervals are generally planar, but occasionally they have flute casts, tool marks, or trace fossils. The lowermost parts of the sandy intervals are occasionally structureless (Ta of Bouma, 1962), grading into parallel laminations (Tb of Bouma, 1962). More commonly, the sandy intervals begin with parallel laminations (Tb). The upper parts of the sandy intervals have current ripples and sometimes convolute bedding or hummocky cross stratification (Tc of Bouma, 1962). The siltier parts of the layers have parallel lamination (Td of Bouma, 1962), and upper surfaces do not appear to have been eroded. However, the muddier parts of the beds (Te of Bouma, 1962) are often absent, indicating possible erosion. Vertical to subvertical burrows occur occasionally in the sandier parts of the beds, and carbonaceous material is commonly present. The layers are continuous over outcrops of 100s of meters. They are interpreted as deposits of dilute turbidity currents.

These turbidites document an upsection shallowing. In the lower part of the section, turbidites show no evidence of reworking by waves, and so are interpreted to have been deposited below wave base. This is in agreement with the shelf to slope setting inferred for the underlying Queyras Marlstone. In the middle part of the section, some medium-grained sandstones display hummocky cross-stratification, which indicates deposition above storm wave base. In the uppermost 20 m of the formation, the upper surfaces of fine- to medium-grained sandstones have symmetrical wave ripple marks, indicating deposition above fair weather wave base. These sedimentary structures indicate that the turbidites were deposited on a shallowing shelf, possibly in a delta-front environment as interpreted for the time equivalent turbidites of the Lower Marine Molasse of central Switzerland (Homewood *et al.*, 1985; Sinclair *et al.*, 1991). The turbidites of the Lower Marine Molasse have alternatively been interpreted as the deposits of a prograding "Normark-type" turbidite fan (Diem, 1986). However, there is not enough evidence in Dévoluy to ascertain whether the Souloise Greywacke was deposited in such an environment.

The beginning of the shallowing from the Queyras Marlstone to the Souloise Greywacke coincides with a notable increase in siliciclastic material in the Souloise Greywacke relative to the Queyras Marlstone. This material includes monocrystalline quartz with straight and undulose extinction, polycrystalline quartz, feldspars, and various types of lithic fragments, most notably serpentinite. The increase in metamorphic debris indicates either (1) that a new source area of siliciclastic material became available, or (2) that progressively more metamorphic rocks were exposed in the source area.

The Lower St-Disdier Arenite

The Lower St-Disdier Arenite does not contain fossils, but is considered as Lower Oligocene (Rupelian) because it conformably overlies the Upper Eocene-Lower Oligocene Souloise Greywacke east of the Median Dévoluy Thrust (Fig. 3) and is overlain by the Chattian (Upper Oligocene) Upper St-Disdier Siltstone (Table I). The Lower St-Disdier Arenite crops out in western Dévoluy and in two northern localities in the hanging-wall of the Median Dévoluy Thrust (Figs. 2, 3). It is at least 125 m thick in its most complete outcrop, in western Dévoluy (Fig. 3). In southwestern Dévoluy, it is present in small outcrops below the Upper St-Disdier Siltstone (Figs. 2, 3); however, it cannot be determined whether the unit was eroded before deposition of the Upper St-Disdier Siltstone or if these few deposits preserve their original thicknesses at this locality.

The lower bounding surface of the Lower St-Disdier Arenite is a progressive unconformity. The erosional hiatus of the unconformity decreases from the west, where the Lower St-Disdier Arenite overlies Senonian limestones, to the east, where the Lower St-Disdier Arenite lies unconformably on progressively younger Tertiary formations (Figs. 2, 3, 5d). In the hanging-wall of the Median Dévoluy Thrust in central Dévoluy, it conformably overlies the youngest deposits of the Souloise Greywacke (Fig. 5d). This progressive unconformity indicates that the western Dévoluy border was uplifted and eroded before or during Rupelian deposition in central Dévoluy. The stratigraphy was previously interpreted in terms of a time-transgressive lateral lithofacies transition between the Lower St-Disdier Arenite and the underlying formations by Gidon *et al.* (1980) and Pairis *et al.* (1983, 1984a). The upper boundary of the Lower St-Disdier Arenite has not been directly observed in the field, although it is inferred in western Dévoluy (e.g., Fig. 3, column d).

The Lower St-Disdier Arenite is a coarse- to fine-grained, green to grey-green sandstone with well-sorted and usually well-rounded grains. The sandstone occurs in 5-150 cm thick beds with massive and planar bedding, tabular and trough cross bedding, and climbing ripples on trough cross bed surfaces which occasionally show current directions opposite to those of the trough cross beds. Bedding surfaces are predominantly planar, but are occasionally concave-up. The lowermost 50 m of section is devoid of silt- or mudstone beds, but these increase in frequency upsection. There is occasional bioturbation in finer-grained beds. The sandstone is composed of locally abundant serpentinite and metamorphic lithic fragments, monocrystalline quartz with straight and undulose extinction, polycrystalline quartz, orthoclase, plagioclase, micas, and glauconite (Waibel, 1990). There is an upsection decrease in carbonate rock fragments.

The continuity between the deposition of the shallow marine upper Souloise Greywacke and the Lower St-Disdier Arenite suggests that the Lower St-Disdier Arenite was also deposited in a shallow marine setting. This hypothesis is supported by the presence of sedimentary structures indicating two directions of transport and the planar bedding surfaces, suggesting that this formation was deposited in a medium- to high-energy upper shoreface (McCubbin, 1982) or a tidal shelf setting. The decrease in petrographic maturity relative to the underlying Souloise Greywacke reflects a nearby metamorphic source area.

The Upper St-Disdier Siltstone

The Upper St-Disdier Siltstone is dated as Upper Oligocene (Chattian) based on the presence of diagnostic charophytes (Pairis *et al.*, 1983; Fabre *et al.*, 1986). The Upper St-Disdier Siltstone crops out in the foot-wall of the Median Dévoluy Thrust (Figs. 2, 3). Although neither its base nor its top crop out, the formation is at least 50 m thick near the village of Bas Gicon in northern Dévoluy, and more than 78 m thick south of Col du Festre in southwestern Dévoluy (Fig. 3, column h). The base of the formation is assumed to be transitional with the Lower St-Disdier Arenite (Fig. 3).

The Upper St-Disdier Siltstone is characterized by three lithofacies: red or greenish-red colored mud- and siltstones; lenticular, fining-up, green colored, medium- to coarse-grained sandstones; and nodular to massive, red to buff colored siltstone to fine-grained sandstone.

The mud- and siltstone lithofacies is volumetrically the most significant of the three lithofacies. It is present in all outcrops of the formation and is continuous over the extent of an outcrop. It is very thinly bedded to massive. The transition between layers of different colors occurs over a few centimeters.

The lenticular sandstone lithofacies incises the mud- and siltstone lithofacies as a series of channels. The channels are laterally symmetrical and are enclosed by the mud- and siltstones. The tops of the channels are sub-planar. The channels have moderate width-to-depth ratios (100+m wide, 1-10 m deep), and contain moderately- to well-sorted sand. Common internal structures include sigma cross beds, trough cross beds, and planar beds. Current ripples on the tops of many of the sandstones indicate paleocurrents subparallel to the larger cross beds. These deposits are petrographically and texturally less mature than the sandstones of the Lower St-Disdier Arenite. They contain rounded to non-rounded clay rip-up clasts at their base, and abundant serpentinite, undular and polycrystalline quartz, lithic fragments, and feldspars.

The nodular to massive silt- and fine-grained sandstone lithofacies is carbonate-cemented and commonly has root casts (rhizoliths). This lithofacies is bounded above and below by the mud- and siltstone lithofacies. Upper and lower surfaces are transitional. The beds of this lithofacies are coarser-grained than the beds of the mud- and siltstone lithofacies. The beds, which have a tabular geometry and planar tops and bottoms, are 10-100 cm thick and have crude fining-up trends. The beds are continuous over the length of a given outcrop, which can reach several hundred meters along strike. The nodular nature of these layers (when present) and the rhizoliths within the layers are indictive of subaerial exposure and calichification (Esteban and Klappa, 1983).

This association of these three lithofacies is typical of an alluvial floodplain (Cant, 1982). The mud- and siltstone lithofacies is interpreted as overbank deposits. The lenticular sandstone lithofacies is interpreted as channelized fluvial deposits of a meandering stream system with bedload to mixed-load fills. The nodular to massive silt- and sandstone lithofacies is interpreted as alluvial deposits, possibly crevasse splays altered by soil formation (caliche).

Neogene structural evolution

Neogene deformation in Dévoluy was predominantly compressional, dominated by large-scale open folding and the development of the Median Dévoluy Thrust. Steep N-S and NE-SW striking faults cut through central Dévoluy. It is reasonable to assume that the main deformation took place sometime after the mid-Oligocene, when the main Alpine compression reached the external zones (Platt *et al.*, 1989). The age of deformation can be stratigraphically constrained as postdating deposition of the Upper St-Disdier Siltstone (Upper Oligocene).

The Median Dévoluy Thrust

The Median Dévoluy Thrust (Gidon and Pairis, 1976; Gidon *et al.*, 1980) runs from immediately northwest of Mt. St-Gicon to the southwest, where it exits the area east of Col du Festre (Fig. 4). It has an average 000-20E orientation (Fig. 8a). It places Senonian rocks over Upper Eocene and Oligocene rocks in northern and southern Dévoluy (Mercier and Neveu, 1956), and Upper Eocene rocks over Oligocene rocks in central Dévoluy (Fig. 2).

The Median Dévoluy Thrust is exposed as a flat-on-flat thrust at two localities in northern Dévoluy (Bas Gicon, Puy de Rioupes, Fig. 4). At Bas Gicon, it emplaces the Souloise Greywacke on the Upper St-Disdier Siltstone (Fig. 2). A 2-5 m thick shear zone overlies the fault surface. It is characterized by small (< 5 cm thick) stacked synthetic duplexes comprising folded and discontinuous sandstone, siltstone, and mudstone beds of the Souloise Greywacke associated with calcite veins and slickenfibers (Figs. 7c, 7h). At Puy de Rioupes, the Median Dévoluy Thrust is a discrete plane emplacing the Souloise Greywacke and the Lower St-Disdier Arenite upon the Upper St-Disdier Siltstone. Calcite slickenfibers on the main fault surface at both localities show tightly grouped W-directed displacement directions (Fig. 8a). The average compressional axis ($\sigma 1$) of these data is oriented to 270° (Fig. 8c). Slickenfibers on synthetic faults provide a wider spread of displacement directions (Fig. 8b). However, the overall compression on the minor faults is the same ($\sigma 1$ = 271°; Fig. 8d).

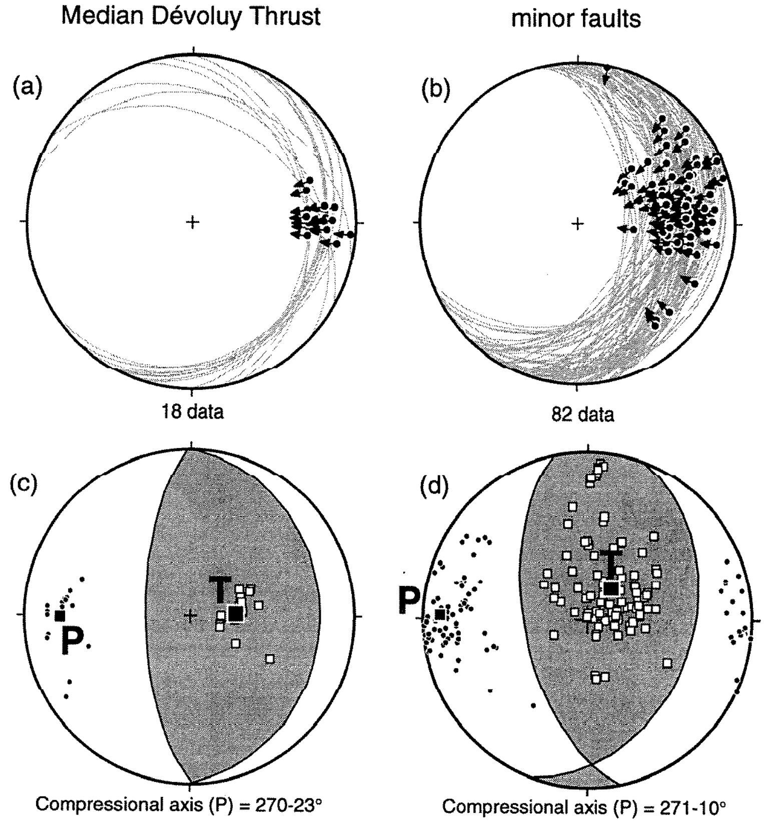

Fig. 8. – (a, b) Equal area, lower hemisphere stereonets of fault data from (a) the Median Dévoluy Thrust and (b) minor faults associated with the Median Dévoluy Thrust. Data collected at Bas Gicon and Puy de Rioupes (Fig. 4). Great circles are measured orientations of the fault plane; arrows show the movement of the hanging-wall relative to the foot-wall, as measured on slickenfibers. (c, d) Fault plane solutions (linked Bingham axes) for (c) the Median Dévoluy Thrust and (d) minor faults associated with the Median Dévoluy Thrust.

Fig. 8. – Stéréogrammes (canevas de Schmidt, hémisphère inférieur) des données structurales (a) du chevauchement médian du Dévoluy et (b) des failles mineures accompagnant le chevauchement médian du Dévoluy. Les données proviennent de Bas Gicon et Puy de Rioupes (figure 4). Les grands cercles représentent les orientations mesurées du plan de faille ; les flèches montrent le mouvement relatif du toit par rapport au mur, mesuré sur des stries. (c, d) Solutions cinématiques (axes de Bingham assemblés) du jeu (c) du chevauchement médian du Dévoluy et (d) des failles mineures accompagnant le chevauchement médian du Dévoluy.

A narrow zone of moderately well-developed pressure solution cleavage occurs in the Queyras Marlstone around the Median Dévoluy Thrust (Fig. 4). This cleavage has an average orientation of 175-74E (Fig. 9a) in the eastern limb of the Tête de la Tune Syncline and of 177-87W in the western limb of the Gicon Anticline (Fig. 9b). The cleavage is approximately parallel to the fold axial planes. However, it occurs only within 100 m on either side of the Median Dévoluy Thrust as a ductile bead of deformation.

Although foot-wall and hanging-wall cutoffs are difficult to constrain, cross sectional models (Figs. 5a, c, d, e) indicate that the minimum horizontal displacement on the Median Dévoluy Thrust is in the order of 2 to 3 km. This displacement decreases to the north as the thrust cuts upsection, such that its hanging-wall stratigraphy thins. In the north, the thrust steepens to 45°E (Fig. 5a; Gidon and Pairis, 1976) and links into the subvertical Aspres-lès-Corps Fault (Gidon and Pairis, 1976; Gidon *et al.*, 1980; Fabre *et al.*, 1986). Post-Oligocene movement on the Aspres-lès-Corps Fault was dextral, which is consistent with the W-directed compression recorded on the Median Dévoluy Thrust.

On a regional scale the Median Dévoluy Thrust links to the south with the Digne Thrust (Fig. 1a; Gidon and Pairis, 1976; Gidon *et al.*, 1980; Fabre *et al.*, 1986), which records 20 km of Mio-Pliocene SW-directed displacement (Ehtechamzadeh-Afchar and Gidon, 1974; Arnaud *et al.*, 1977; Fry, 1989). Therefore, displacement on the Median Dévoluy Thrust is inferred to be Mio-Pliocene.

Folds in Northern Dévoluy

All the folds in northern Dévoluy (Fig. 4) are west-verging, trend N-S to NNW-SSE, and have shallowly to moderately south-plunging axes (Figs. 9a-c). The folds have half-wavelengths of 1 to 4 km and amplitudes of up to 500 m. These folds are oriented approximately perpendicular to the transport direction recorded on the Median Dévoluy Thrust and their geometry is consistent with top-to-the-west tectonic transport. They are interpreted as fault-propagation folds that developed ahead of the Median Dévoluy and other thrusts.

The Tête de la Tune Syncline (TTS; axis 171-25; Fig. 9a), the foot-wall syncline of the Median Dévoluy Thrust, is only completely visible at the northern end of Dévoluy, because its eastern limb is overthrust north of the village of St-Disdier (Fig. 4). Anticlines occur in the hanging-wall of the Median Dévoluy

Thrust at Mt. St-Gicon (GA; axis 177-20; Fig. 9b) and on the Plateau d'Auroze where a broad open anticline trends approximately N-S (Fig. 4). The Gicon Anticline terminates in central Dévoluy against N-S and NNE-SSW faults (Fig. 4).

The NNE-SSW trending Rourebean Syncline (RS) and the NNW-SSE trending Puy de Rioupes Syncline occur in the immediate hanging-wall of the Median Dévoluy Thrust, between the thrust and the N-S oriented, subvertical Malmort Fault (Fig. 4).

The Col de l'Aup Syncline (CAS; axis 181-14; Fig. 9c) lies east of the Gicon Anticline (Fig. 4). The northern hinge zone contains small, meter-scale folds (Fig. 6c). The Col de l'Aup Syncline cannot be followed through the zone of N-S and NNE-SSW faults in central Dévoluy (Fig. 4), but is considered to link to the St-Etienne Syncline (SES) in southeastern Dévoluy (Gidon and Pairis, 1976).

The distribution of cleavage in Dévoluy (Fig. 4) clearly demonstrates that its development was not associated with folding. Instead, pressure solution cleavage occurs in zones consistently associated with faults such as the Median Dévoluy Thrust, the Les Bourrettes Fault, the Malmort Fault, and the Banards and Grand-Combe Klippen (Fig. 4). Cleavage therefore developed in zones of distributed strain around faults of all kinds (thrusts and strike-slip). The only cleavage that is not clearly associated with a fault is a well developed pressure solution cleavage (average orientation 349-88E; Fig. 9c) in the Queyras Marlstone in the western limb of the Col de l'Aup Syncline (Fig. 4). The cleavage transects the fold axis by 12° in a counter-clockwise sense. Based on this transection and on fault-cleavage relations observed elsewhere in Dévoluy, the cleavage is thought to be unrelated to folding and may indicate the presence of an unidentified fault, perhaps the northward continuation of the Les Bourrettes Fault (Fig. 4).

NE-SW subvertical faults in central Dévoluy

Two sets of subvertical faults, trending 000-010° and 030-045° respectively, cut across central Dévoluy in the hanging-wall of the Median Dévoluy Thrust. Where the fault sets intersect, they divide the hanging-wall into lozenge-shaped blocks (Fig. 4).

The NE-SW faults form a zone north and northwest of St-Etienne (the St-Etienne Fault Zone). Northern Dévoluy is downthrown relative to southeastern Dévoluy across the fault zone and the zone was itself uplifted relative to both southeastern and northern Dévoluy (Fig. 2). The faults accommodate maximum displacement in the hinge zone of the St-Etienne Syncline and Col de l'Aup Syncline (Fig. 2), suggesting that they developed during folding. They die out in the Senonian strata exposed northeast and southwest of the zone (Fig. 4).

In two of the fault-bounded blocks of the St-Etienne Fault Zone, Senonian limestones and the Nummulitic Limestone lie in NNE-SSW trending, open anticlines (Fig. 4). The folds have 1 km half-wavelengths and 50-100 m amplitudes. They are characterized by broad, flat hinge zones across the fault blocks and moderately-dipping limbs next to faults, which suggests that the limbs were steepened during fault activity. These medium-scale folds refold smaller, W-E to NW-SSE trending folds (Figs. 4, 10a).

The thick Senonian limestones of the Plateau d'Auroze disappear abruptly across the northwestern edge of the St-Etienne Fault Zone (Fig. 4), where at least 150 m of downthrow to the northwest was accommodated. This thinning

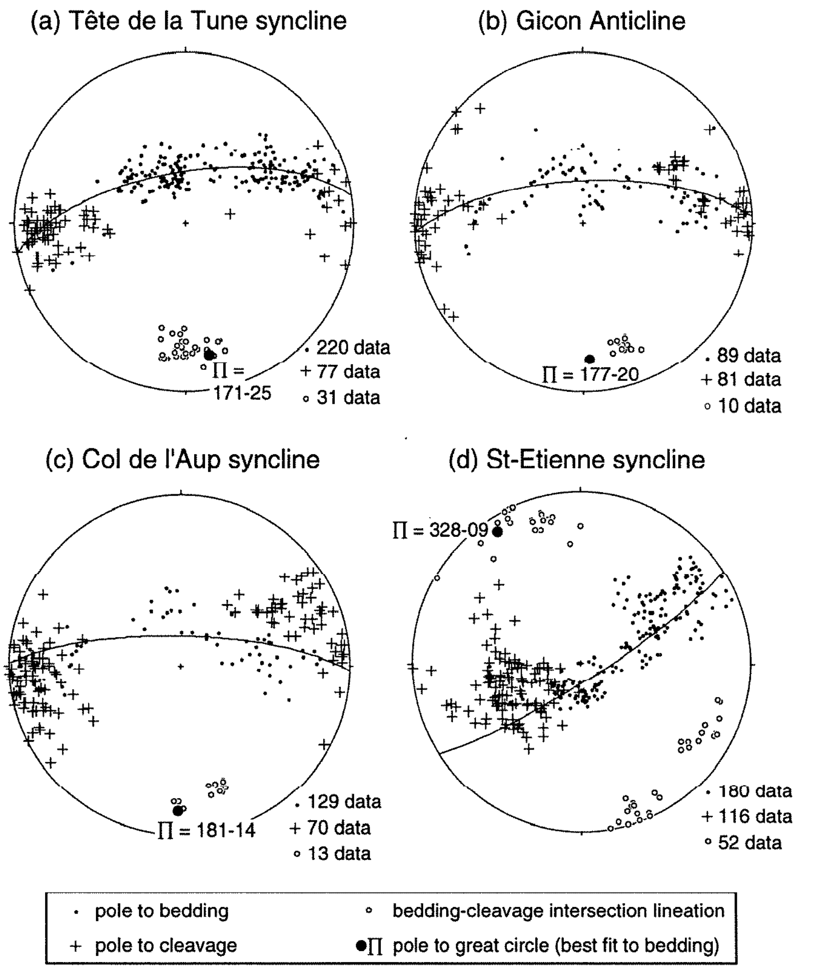

Fig. 9. – Equal area, lower hemisphere stereonets of structural data associated with (a) the Tête de la Tune Syncline (TTS), (b) the Gicon Anticline (GA), (c) the Col de l'Aup Syncline (CAS), and (d) the St-Etienne Syncline (SES).

Fig. 9. – Stéréogrammes (canevas de Schmidt, hémisphère inférieur) des données structurales accompagnant (a) le Synclinal de la Tête de la Tune (TTS), (b) l'Anticlinal du Gicon (GA), (c) le Synclinal du Col de l'Aup (CAS), et (d) le Synclinal de St-Etienne (SES).

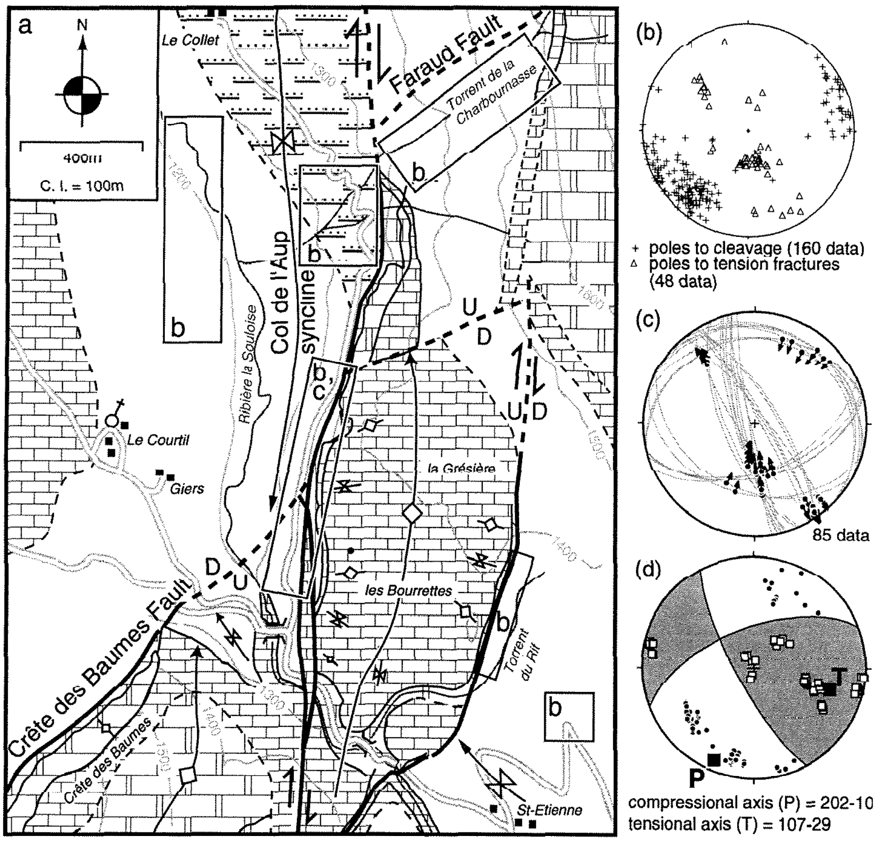

Fig. 10. – (a) Detailed map (located in fig. 2) of Les Bourrettes showing locations of data shown in 10b-d. The Les Bourrettes Fault runs approximately N-S through center of map. Symbols as in fig. 3. (b, c) Equal area, lower hemisphere stereonets of (b) cleavage and fracture and (c) fault data (great circles are measured orientations of fault planes; arrows show movement of the hanging-wall relative to the foot-wall, as measured on slickenfibers). (d) Fault plane solution (linked Bingham axes) for Les Bourrettes.

Fig. 10. – (a) Carte détaillée (localisée figure 2) des Bourettes montrant les stations de mesures présentées en 10b-d. La Faille des Bourrettes est approximativement N-S, passant par le centre de la carte. Les symboles sont identiques à ceux de la figure 3. (b, c) Stéréogrammes (canevas de Schmidt, hémisphère inférieur) des données structurales d'orientation (b) de la schistosité et des fractures et (c) des failles aux Bourettes. (c) Les grands cercles représentent les plans de faille ; les flèches, le mouvement relatif du toit par rapport au mur, mesuré sur des stries. (d) Solution cinématique (axes de Bingham assemblés) aux Bourettes.

of the hanging-wall stratigraphy of the Median Dévoluy Thrust reflects the fact that the Median Dévoluy Thrust cuts upsection from south to north across Dévoluy. Therefore, the fault zone is considered to be a "hanging-wall drop fault" zone (*sensu* Butler, 1982) that accommodated the stratigraphic climb. It may coincide with an older geographic feature.

N-S subvertical faults

The two principal N-S trending faults, the Les Bourrettes and Malmort Faults, can be traced from northern Dévoluy into the St-Etienne Fault Zone (Fig. 4). Their sense of downthrow occasionally switches across their intersections with NE-SW faults (Fig. 4), indicating that the two fault systems developed synchronously (e. g., Schreurs, 1994). To the south, the N-S faults curve to NE-SW before dying out in the Plateau d'Auroze (Fig. 4). Minor structures associated with these two N-S faults provide information on their kinematics.

Immediately adjacent to the Les Bourrettes Fault (Fig. 10a), there is a well-developed, local, planar pressure solution cleavage (average orientation 128-74W; Fig. 10b) in the Queyras Marlstone. The cleavage is oriented approximately 35° counter-clockwise to the trend of the fault, and is highly oblique to the trend of the Col de l'Aup Syncline (fold axis = 181-14S) at this locality, indicating a dextral component of shear (Figs. 10a, b). A tension fracture set near the fault is oriented ENE-WSW and dips variably to the NNW and SSE (Fig. 10b). These fractures are filled with massive calcite and exhibit no slip. One minor fault set, oriented NNW-SSE and dipping WSW and ENE (Fig. 10c), has calcite slickenfibers which show pure normal to oblique right-lateral displacement (Fig. 10c). A second minor fault set is oriented predominantly WNW-ESE to NW-SE, with planes dipping to the SW and NE. These planes have calcite slickenfibers with reverse displacement (Fig. 10c).

The fault data at Les Bourrettes indicate a SSW-oriented compressional axis ($\sigma 1$ = 202-10) and an ESE-oriented extensional axis ($\sigma 3$ = 107-29) (Fig. 10d). These orientations, as well as the orientations of the fractures, are consistent with dextral shear on the N-S oriented Les Bourrettes Fault, as inferred from the cleavage. This fault also has a down-to-the-west displacement of several hundred meters (Fig. 5d).

The Malmort Fault (003-82W; Figs. 11a, b) has no fiber data, but at one locality (b, Fig.11) an intensely developed pressure solution cleavage (average orientation 329-88E; Fig. 11b) has shear bands that record N-S oriented dextral strike-slip (Figs. 7e, j). Further north, the N-plunging Malmort Syncline (fold axis 342-08; Fig. 11c) lies in the western fault block (Fig. 11a). Cleavage (average orientation 148-88E) occurs predominantly in the eastern limb of the fold and dies out to the west. The cleavage transects the fold axis by 14° and is considered to be related to dextral strike-slip on the Malmort Fault. Low-angle tension fractures oriented approximately perpendicular to the cleavage (Fig. 11c) indicate that the extensional axis was subvertical. In area d (Fig.11a), a thrust fault (150-35E) that places the Pierroux Conglomerate over the Queyras Marlstone branches from the Malmort Fault. No fibers are present on the fault surface, but cleavage developed within 5 m of the fault is oriented 155-80E (Fig. 11d), indicating that the fault is indeed a thrust. Minor fault planes west of the thrust and east of the Malmort Fault have a wide range of orientations and show both strike-slip and oblique displacement

(Fig. 11e). Kinematic analysis of these faults shows a SW-directed ($\sigma 1$ = 220-13) compressional axis and a subvertical tensional axis ($\sigma 3$ = 038-77) (Fig. 11f). In summary, all the minor structures associated with the N-S Malmort Fault indicate that it accommodated a dextral displacement within a SW-directed compressional environment. The fault also has a component of downthrow to the west of at least 30 m (Fig. 5d).

The data from the Les Bourrettes and Malmort Faults show that in north-central Dévoluy, a component of dextral shear and downthrow to the west occurred on N-S oriented faults within the hanging-wall of the Median Dévoluy Thrust. The thrust itself records westward thrusting (Figs. 8a, c). We therefore propose that in this area, regional SW-directed compression was partitioned into N-S dextral shear and W-directed thrusting.

Compressional structures in south-eastern Dévoluy

The open, west-facing St-Etienne Syncline (SES) trends NW-SE (Fig. 4) and plunges shallowly NW (axis 328-09; Fig. 9d). Two klippen, the Banards Klippe (Gidon *et al.*, 1980) to the south and the Grand-Combe Klippe to the north, are present in the eastern limb of the St-Etienne Syncline at Col de Rabou (Figs. 2, 4, 12a). The Banards Klippe is bounded by the Banards Thrust (Gidon *et al.*, 1980). The Grand-Combe Klippe is bounded by the Grand-Combe Thrust.

These klippen consist of overturned, E-dipping Cretaceous and Tertiary strata and lie on W-dipping Nummulitic Limestone and Queyras Marlstone (Fig. 12a). Some blocks of klippen material have landslipped down the west-dipping Queyras Marlstones on NNE-SSW oriented, WNW-dipping normal faults that sole into the underlying fault plane (Fig. 12a). The present-day geometry (Fig. 12a) indicates that the klippen were emplaced onto Queyras Marlstones and were subsequently rotated on the eastern limb of the St-Etienne Syncline (Fig. 5e). Therefore, the rotational effects of the St-Etienne Syncline have been removed from the fault data.

When kinematic data from the Banards Thrust and Grand-Combe

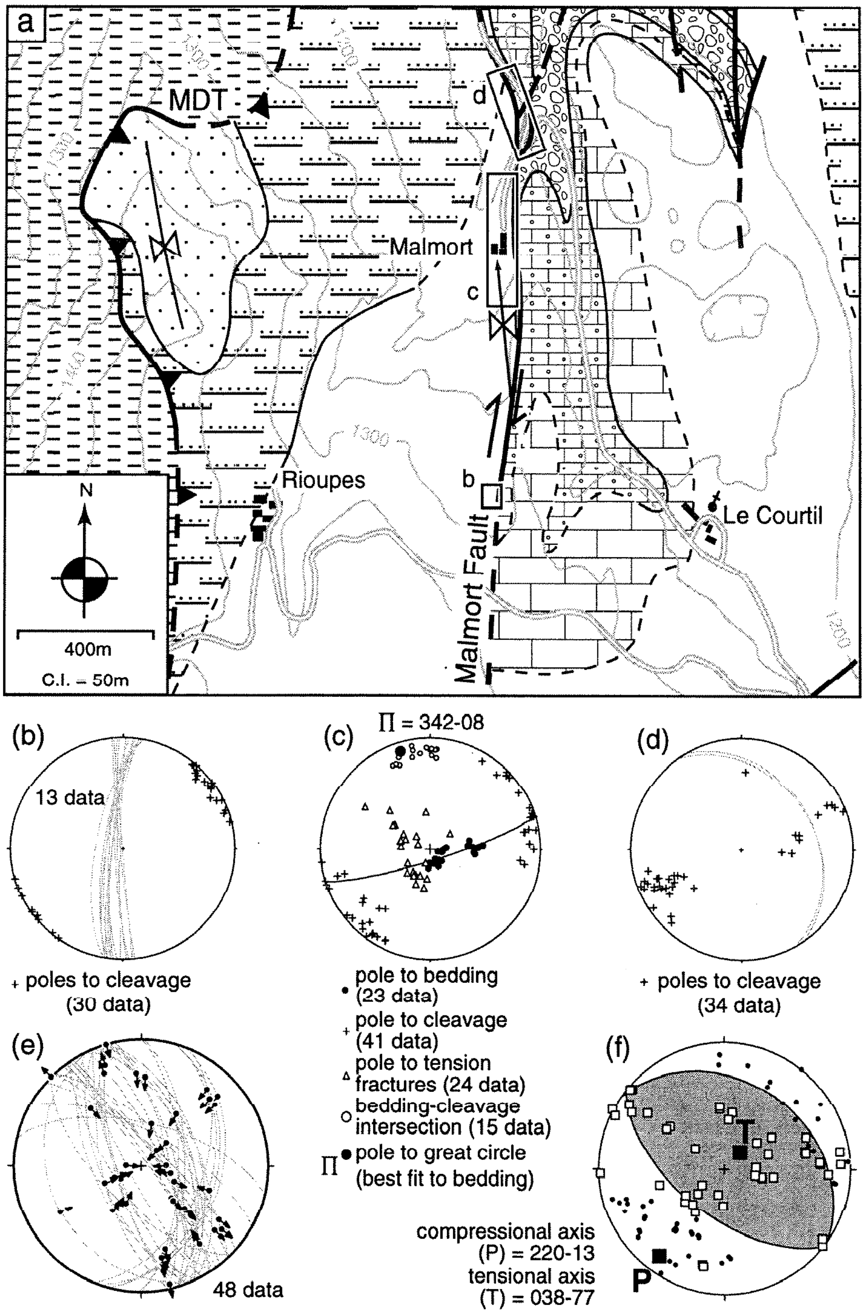

Fig. 11. – (a) Detailed map (located in fig. 2) of the Malmort area showing locations of data shown in 11b-e. Symbols as in fig. 2. (b-e) Equal area, lower hemisphere stereonets of structural data. (b) Malmort Fault and shear band (Figs. 7d, i) data. No slip data is available from the Malmort Fault. (c) Bedding, cleavage, bedding-cleavage intersection lineation, and fracture data west of the Malmort Fault. (d) Thrust fault and cleavage data and (e) minor fault data north of Malmort village (great circles are measured orientations of fault planes; arrows show movement of the hanging-wall relative to the foot-wall, as measured on slickenfibers. (f) Fault plane solution (linked Bingham axes) for the Malmort minor faults.

Fig. 11. – Carte détaillée (localisée figure 2) des environs de Malmort montrant les stations des mesures présentées en 11b-e. Les symboles sont identiques à ceux de la figure 2. (b-e) Stéréogrammes (canevas de Schmidt, hémisphère inférieur) des données structurales. (b) Mesures de la Faille de Malmort et des bandes de cisaillement (cf. figures 7d, i). Il n'y a pas de données de stries liées à la Faille de Malmort. (c) Données pour la surface des couches, la schistosité, la linéation d'intersection couche-schistosité, et les fractures à l'ouest de la faille de Malmort. (d) Mesures des orientations d'un chevauchement et de la schistosité et (e) données structurales des failles mineures au nord du village de Malmort (les grands cercles montrent les orientations de plan de faille normale mesurées; les flèches montrent le mouvement relatif du toit par rapport au mur, mesuré sur des stries. (f) Solution cinématique (axes de Bingham assemblés) de Malmort.

Thrust are corrected, the restored thrust plane has an average NW-SE strike and NE dip (Fig. 12b). Variations in this orientation occur because of open warps in the fault planes. Slickenfibers show displacement orientations varying from north to south, with an overall displacement to the southwest (Fig. 12b). The corrected compressional axis of these fibers ($\sigma 1$) is 215-26 and the corrected tensional axis ($\sigma 3$) is 001-59 (Fig. 12c).

A pressure solution cleavage is intensely developed beneath the Banards Klippe. It dies out away from the klippe and is considered to be fault-related. However, its corrected average orientation is 162-81E (Fig. 12d), 35° oblique to the corrected compressional axis of the Banards and Grand-Combe Thrusts. Furthermore, kinematic analysis of calcite slickenfibers on the backs of shear bands in the Queyras Marlstones immediately below the Banards Thrust shows overall W-directed displacement. These orientations are counterclockwise from the compression recorded on the Banards and Grand-Combe Thrusts, and indicate a strong component of W- to WSW-directed compression. It seems most likely that the lack of a clear correlation between the cleavage and the displacement on the klippen is the result of a differential response to the later folding of both.

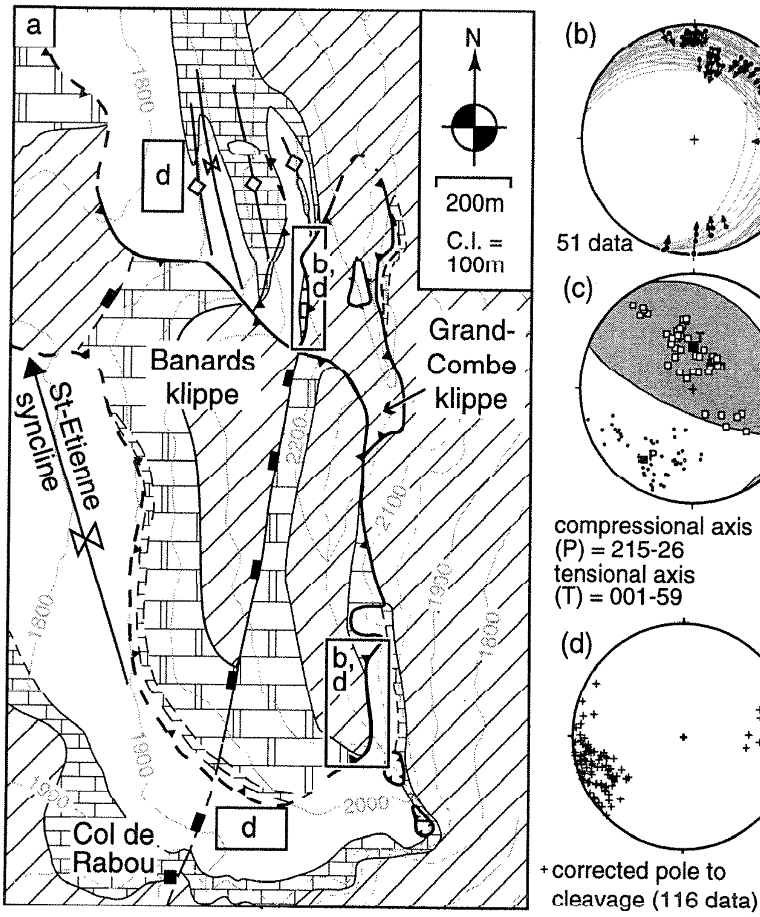

Fig. 12. – (a) Detailed map (located in fig. 2) of the Banards and Grand-Combe Klippen showing locations of data shown in 12b, d. Symbols as in fig. 3. (b) Equal area, lower hemisphere stereonet of corrected fault data. Data was rotated twice to compensate for the younger NE-plunging St-Etienne Syncline. Great circles are measured orientations of the fault plane; arrows show the movement of the hanging-wall relative to the foot-wall, as measured on slickenfibers. (c) Fault plane solution (linked Bingham axes) for the Banards and Grand-Combe Klippen, corrected for folding. (d) Equal area, lower hemisphere stereonet of corrected cleavage data. Data was rotated twice to compensate for the younger NE-plunging St-Etienne Syncline.

Fig. 12. – (a) Carte détaillée (localisée figure 2) des Klippes de Banards et Grand-Combe montrant les stations des mesures présentées en 12b, d. Les symboles sont identiques à ceux de la figure 3. (b) Stéréogramme (canevas de Schmidt, hémisphère inférieur) des données de faille. Les données sont corrigées deux fois pour compenser l'effet du Synclinal de St-Etienne, plus jeune. Les grands cercles montrent les orientations de plan de faille. Les flèches montrent le mouvement relatif du toit par rapport au mur, mesuré sur des stries. (f) Solution cinématique (axes de Bingham assemblés) du jeu des Klippes de Banards et Grand-Combe. (d) Stéréogramme (canevas de Schmidt, hémisphère inférieur) des données de schistosité corrigées. Les données sont corrigées deux fois pour compenser l'effet du Synclinal de St-Etienne, plus jeune.

Discussion

Pre-Priabonian deformation

The concentration of pre-Senonian and Eocene folding and faulting in northern Dévoluy indicates that tectonism was most intense there and can be related to periods of alternating sinistral and dextral strike-slip movement on the Aspres-lès-Corps Fault (Gidon and Pairis, 1976). The sinistral movement, which was more prevalent than dextral movement in the late Cretaceous (Ford and Stahel, 1995), would have caused N-S compression and W-E extension, and the subordinate dextral movement would have caused W-E compression. In this scenario, the sinistral movement resulted in W-E oriented pre-Senonian folds and down-to-the-east and down-to-the-west Paleocene to late-Eocene extensional faults, while the dextral movement resulted in N-S oriented Eocene folds.

The dextral activity on the Aspres-lès-Corps Fault may have been contemporaneous with Eocene (Ford, 1996) uplift and folding of the Pelvoux basement and its cover ten kilometers to the east of Dévoluy (Fig. 1). Such deformation could have caused uplift of Senonian limestones NE of Dévoluy, which were then eroded and redeposited in the Pierroux Conglomerate alluvial fan. Clasts of crystalline rock derived from the Pelvoux massif are not seen in Dévoluy, which indicates that it was not an active source for the sediments here.

Priabonian deepening

The upsection transition from the shallow marine Nummulitic Limestone to the deeper marine Queyras Marlstone during the Priabonian reflects a deepening of the Dévoluy region. The Nummulitic Limestone is lithologically correlated with the time-transgressive Alpine

Nummulitic Limestone. The Queyras Marlstone corresponds to the Globigerina Marls and Marnes Bleues elsewhere in the western Alps. These deposits have been attributed to a period of east to west marine transgression around the external Alps. Dévoluy is located at the western edge of this transgression (Fig. 13). The transgression initiated the "underfilled" phase of foreland basin evolution, during which the rate of creation of accommodation space was greater than the rate of sediment supply.

The Alpine transgression was caused by subsidence associated with downbending of the lithosphere when it was loaded by the emplacement of internal tectonic units (e.g., Kerckhove *et al.*, 1980; Pairis *et al.*, 1984; Homewood *et al.*, 1986; Herb, 1988; Pairis, 1988; Coward and Dietrich, 1989; Platt *et al.*, 1989; Sinclair *et al.*, 1991). In Champsaur, 15 km east of Dévoluy, subsidence is estimated at .04 mm/yr during deposition of the Nummulitic Limestone and .08 mm/yr during deposition of equivalents of the Queyras Marlstone (Crampton, 1992). Such rates are approximately equivalent to the rates of accumulation of cool water carbonates (Bosscher, 1992; Jones and Desrochers, 1992), and thus the system could, theoretically, have kept pace with subsidence. However, a eustatic sea level rise during the Priabonian (Table I; Haq *et al.*, 1988) may have reinforced the effects of subsidence. In any case, the carbonate system could not keep up and the basin experienced deepening. In Dévoluy, extensional faulting may have increased subsidence and enhanced deepening.

The predominance of detrital carbonate sediments in Dévoluy indicates a local source of sediment during this time. The upsection influx of siliciclastic debris in the Queyras Marlstone indicates a new source of sediments in the late Priabonian.

Late Priabonian through late Oligocene marine shallowing and continental deposition

The deepening was followed by shallowing and, ultimately, continental deposition in the late Priabonian through the Oligocene, as recorded by the Souloise Greywacke, the Lower St-Disdier Arenite, and the Upper St-Disdier Siltstone. The same depositional trend is recorded in the Lower Marine and Lower Freshwater Molasse of western Switzerland (Homewood *et al.*, 1985, 1986; Diem, 1986) and in the Annot-Barrême basin fragments in SE France (Elliott *et al.*, 1985). Dévoluy is the westernmost preserved foreland basin fragment to completely record this transition (Fig. 13). This period of Oligocene regression (Kerckhove *et al.*, 1980; Pairis *et al.*, 1984) and continental deposition is accompanied by a shift of sedimentary depocenters to the west (Fig. 13; Elliott *et al.*, 1985).

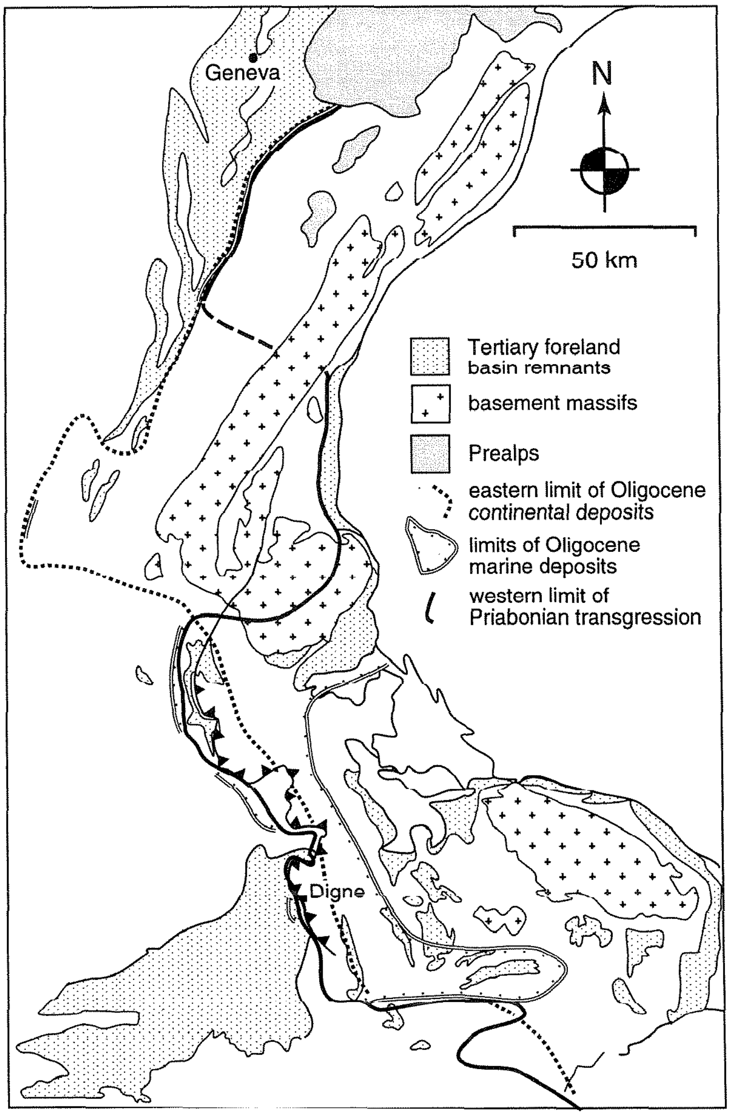

Fig. 13. – Map showing interpreted boundaries of Tertiary deposits of western Alpine foreland basin. Dévoluy is located in an embayment south of the Pelvoux massif at the western boundary of Priabonian transgression and the eastern boundary of Oligocene continental deposition. Modified after Kerckhove *et al.* (1980), Pairis *et al.* (1984b), and Pairis (1988).

Fig. 13. – Carte montrant les limites interprétées des dépôts tertiaires du bassin d'avant-chaîne des Alpes occidentales. Le Dévoluy est situé dans un golfe au sud du massif du Pelvoux, à la limite occidentale de la transgression priabonienne et à la limite orientale des dépôts continentaux de l'oligocène. Modifiée d'après Kerckhove et al. *(1980), Pairis* et al. *(1984b) et Pairis (1988).*

Lithostratigraphical correlation of the Souloise Greywacke with other time-equivalent Alpine turbidite deposits such as the North Helvetic Flysch and lower most Lower Marine Molasse (Pairis *et al.*, 1984; Homewood *et al.*, 1985, 1986; Diem, 1986), the Champsaur Sandstone (Waibel, 1990), the Annot Sandstone

(Sinclair, 1993), and the Grès de Ville unit in Barrême (Evans, 1987; Evans and Mange-Rajetzky, 1991) has not yet been firmly established. The Lower St-Disdier Arenite is sedimentogically and temporally similar to the upper part of the Lower Marine Molasse in the Swiss Molasse Basin (Homewood *et al.*, 1985, 1986; Diem, 1986). Significant petrographic and sedimentological differences between the Lower St-Disdier Arenite and the Val d'Illiez Sandstone of western Switzerland (Ujetz *et al.*, 1994) make earlier comparisons (Waibel, 1990; Vuagnat, 1947) problematic, and Waibel's (1990) correlation of the shallow marine, shoreface Lower St-Disdier Arenite with the deep marine turbidites of the Champsaur Sandstone is considered misleading because of significant differences in petrography and sedimentology between the two units.

The shallowing in Dévoluy during the early Oligocene indicates that this part of the Alpine foreland basin had reached the "filled" stage of its evolution. Clearly, the rate of sediment supply overtook the rate of creation of accommodation space. However, the reason for this change is enigmatic because the shallowing was contemporaneous with emplacement of the Penninic nappes east and southeast of Dévoluy (Arnaud *et al.*, 1977; Trümpy, 1980; Dewey *et al.*, 1989; Fry, 1989; Ford, 1996). If subsidence in Dévoluy increased due to emplacement of the Penninic nappes, the rate of sediment supply due to erosion of the nappes must have increased concomittantly in order to maintain shallowing conditions. These nappes are the likely source of the serpentinite and other siliciclastic debris in the Souloise Greywacke, the Lower St-Disdier Arenite, and the Upper St-Disdier Siltstone (Waibel, 1990). The unconformity at the base of the Lower St-Disdier Arenite indicates that shallowing in western Dévoluy was in fact enhanced by local uplift, probably due to foreland propagating thrusts at depth. A fall in eustatic sea level at the Eocene-Oligocene boundary (Table I; Haq *et al.*, 1988) may have temporarily reinforced the basin shallowing, but eustasy does not seem to have been a general controlling factor in basin shallowing since the ensuing rise in eustatic sea level and the reestablishment of deep marine conditions in the early Oligocene (Table I; Haq *et al.*, 1988) are not recorded in Dévoluy.

The Upper St-Disdier Siltstone is sedimentologically and temporally correlatable with the Lower Freshwater Molasse of the Swiss Molasse Basin (Homewood *et al.*, 1985, 1986) and with part of the Molasse Rouge of the Barrême basin (Evans, 1987; Evans and Mange-Rajetzky, 1991). This transition to continental sedimentation in the mid Oligocene represents the change to the "overfilled" stage of foreland basin evolution. Sedimentation prevented significant amounts of subaerial erosion in Dévoluy. The shift in conditions is time-equivalent with a significant eustatic sea level fall in the mid-Oligocene (Table I; Haq *et al.*, 1988). Homewood *et al.* (1985, 1986) suggest that this sea level fall may have played a significant role in the transition from shallow marine to continental deposition in the Molasse Basin. This eustatic fall may also have been responsible for the marine to continental transition in Dévoluy. However, tectonic uplift must have offset the punctuated rise in eustatic sea level during the late Oligocene (Table I; Haq *et al.*, 1988), such that marine conditions were not reestablished.

Neogene folding and faulting

SW-directed compression migrated westward across Dévoluy in post-late Oligocene times, whereby emplacement of thrust sheets in SE Dévoluy predates folding (Fig. 5e). Across Dévoluy, active folding then preceded thrusting on the Median Dévoluy Thrust (Figs. 5a, c, d). Westward thrusting on the Median Dévoluy Thrust was coupled with dextral shear and down-to-west offset on N-S faults in the hanging-wall. This partitioning of SW compression occurs where the Median Dévoluy Thrust begins to steepen and links with the Aspres-lès-Corps Fault. It may have been triggered by a combination of a weakening of deformation northward and the influence of dextral movement (Gidon and Pairis, 1976) on the Aspres-lès-Corps Fault. The clockwise curvature of the SES-CAS axial trace towards the north reflects both of these influences. The fact that the Median Dévoluy Thrust cuts up-stratigraphy toward the north until Mt. St-Gicon (Fig. 2) also documents the overall decrease in shortening. At Mt. St-Gicon, the abrupt reappearance of Senonian limestones in the Median Dévoluy Thrust hanging-wall suggests that this block was a palaeotectonic high within the basin (Gidon and Pairis, 1976). This interpretation is supported by the facts that the Nummulitic Limestone was affected by syn-depositional extensional faults and that it onlaps the high (Fig. 5b).

The cleavage found in Dévoluy is best developed in the Queyras Marlstone within a few tens of meters of faults and is not spatially related to folds. Its orientation is strongly dependent on the sense of displacement on the faults. Therefore, the cleavage is thought to have formed in a ductile bead (Cooper and Trayner, 1986) or zone of distributed strain around the faults. The fact that the cleavage orientation is approximately parallel to the axial planes of regional folds in northern and southeastern Dévoluy is interpreted to indicate the close temporal relationship between faulting and folding.

Regional significance

Correlation of Tertiary stratigraphy around the western Alps shows that Dévoluy was part of the larger Alpine foreland basin (Kerckhove *et al.*, 1980; Pairis *et al.*, 1984; Pairis, 1988 ; Fig. 13). The complete Eocene-Oligocene evolution is only preserved in Dévoluy, the Molasse Basin of western Switzerland, and the Barrême basin of SE France, although the early history is also recorded in the Champsaur and Annot foreland basin remnants of the southern Chaînes Subalpines (Kerckhove *et al.*, 1980; Pairis *et al.*, 1984; Pairis, 1988; Fig.13). Figure 13 shows that the Pelvoux, Grandes Rousses, and southern Belledonne basement massifs formed a significant high which impinged on the migrating basin and eventually cut off the southern branch from the northeastern branch of the basin. Dévoluy was located in an embayment southwest of the Pelvoux high (Fig. 13). The foreland basin stratigraphy south and west of the Pelvoux massif is thinner than that to the north (Homewood *et al.*, 1986). Therefore, the Swiss Molasse Basin is thought to record the principal frontal loading of the European plate by the Alpine orogenic wedge, while the western foreland basin records a significantly smaller, lateral loading of the European plate by the same load.

Across the southern Chaînes Subalpines, kinematic data and shortening estimates indicate a northward decrease in WSW-directed shortening (Fry, 1989). The shortening on the Digne Thrust is estimated at 20 km (Ehtechamzadeh-Afchar and Gidon, 1974; Arnaud *et al.*, 1977). In Dévoluy, the shortening on the Median Dévoluy Thrust is estimated to be 2-3 km and decreases to the north, terminating into the Aspres-lès-Corps Fault (Fig. 5). Therefore post-Oligocene deformation in Dévoluy is the northernmost record of southern Chaînes Subalpines shortening. Thrusting in the southern Chaînes Subalpines is of the same age as in the northern Chaînes Subalpines (post mid-Oligocene to Pliocene; Platt *et al.*, 1989). However, kinematics and displacement estimates for the northern Chaînes Subalpines (e.g., Butler, 1984, 1985; Butler *et al.*, 1986; Ménard and Thouvenot, 1986; Mugnier *et al.*, 1987; Gratier *et al.*, 1989; Guellec *et al.*, 1990; Mugnier *et al.*, 1990; Butler, 1992) indicate NW to WNW shortening of between 70-80 km and 120 km, significantly greater and with a different orientation than seen in the southern Chaînes Subalpines. Thus, there is a clear break in structural continuity between Dévoluy and the northern Chaînes Subalpines. The external fold and thrust belt of the Western Alps is therefore not a continuous arc but was generated by two distinct tectonic transport directions, one toward the NW-WNW and one toward the SW-WSW (Ford *et al.*, 1995).

Conclusions

The Dévoluy basin records the complex evolution of the external western Alpine domain from the late Mesozoic through the Cenozoic. The evolution comprises pre-Senonian folding and faulting, sedimentation in the late Senonian, renewed folding and faulting in the early Tertiary, the development of the western Alpine foreland basin in the late Eocene through Oligocene, and a final phase of folding and faulting in the Mio-Pliocene. The Aspres-lès-Corps Fault had a significant influence on all stages of basin evolution and subsequent deformation.

Pre-Senonian tectonism is represented by W-E to NE-SW oriented folds which show N- to NW-directed compression. The thick Senonian limestones which unconformably overlie these folds were deposited during a poorly understood period of sedimentation in the external Alps (Baudrimont and Dubois, 1977).

Eocene folding was related to strike-slip movements on the Aspres-lès-Corps Fault, and was contemporaneous with uplift of the Pelvoux massif. The folds predate deposition of the continental Pierroux Conglomerate. Extensional faults in northern Dévoluy were active prior to and during deposition of the Pierroux Conglomerate and the Nummulitic Limestone.

During the late Eocene and Oligocene, Dévoluy evolved as part of the western Alpine foreland basin. The principal factors controlling the evolution were tectonic, both local and orogenic. Changes in eustatic sea level and sedimentation rates also had significant influence on basin infilling. The underfilled stage of foreland basin development is represented by a marine transgression and deeper marine sedimentation during the late Eocene. Dévoluy is the westernmost existing and youngest part of this transgression (Fig. 13). The transgression is the result of the mutually reinforcing effects of tectonic subsidence, syndepositional extensional faulting, and eustatic sea level rise, the combined effects of which outstripped carbonate-dominated deposition. The transition from deepening to shallowing conditions in the early Oligocene represents the filled stage of foreland basin development, when sediment supply overtook creation of accommodation space. This transition was caused by a combination of local and regional tectonic uplift, increased sediment supply, and temporary eustatic sea level fall. Finally, the basin reached overfilled conditions, as evidenced by the late Oligocene continental conditions.

The Mio-Pliocene deformation in Dévoluy documents the arrival of the Alpine deformation front in the external domain. This deformation was characterized by W- and SW-directed thrusting and folding, associated with N-S dextral shear. There is an overall decrease in shortening to the north, where the Median Dévoluy Thrust links into the Aspres-lès-Corps Fault. The dextral shear and the W-directed thrusting on the Median Dévoluy Thrust probably indicate a local partitioning of overall SW-directed compression. This partitioning is thought to be associated with the northward weakening of deformation before it terminates into the dextral Aspres-lès-Corps Fault.

Acknowledgments

This paper is the result of research conducted by LDM as part of the Swiss National Science Foundation Project NFP 21-32115.91. Dr. P. Tricart (Institut Dolomieu, Grenoble) and Dr. H. Sinclair (University of Birmingham) provided insightful reviews of the manuscript which greatly improved its content. Thanks are also extended to Prof. Dr. J. P. Burg, Dr. W. Winkler, and Dr. E. A. Williams of ETH and Dr. Z. Sayer of the University of Durham for their thoughtful comments and helpful revisions on early drafts of the manuscript. J. P. Burg and E. Sauter graciously provided translations into French.

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