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Paleostress from the Préalpes Médianes (Switzerland)

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Abstract

Investigations on paleostress determined from fault-slickenline populations have been carried out in the Préalpes médianes fold-and-thrust belt along the NW border of the Alpine arc in Switzerland, NE of the Rhône valley. The fault-striation sets analyzed here display remarkably high percentages of mutually consistent fault movements. Two different tectonic regimes prevail: the first is a strike-slip environment linked to large N-S trending vertical fault zones with sinistral movements and N110E oriented faults with right lateral displacement. The second type of structural environment is a NE-SW to NNE-SSW trending thrust system associated with the fold development and with a top-to-the-NW movement. The faults described here and their associated stresses may be linked to the fold-and-thrust developments in the Préalpes médianes, or may slightly postdate this tectonic event and be linked with movements during the final emplacement of the prealpine nappes. Comparing paleostress results from faults in the Préalpes médianes with results obtained from earthquake data in the Molasse basin and in the Jura mountains, reveals striking similarities both in fault and stress orientations. No evidence is given here to advocate an extension of strike-slip faults into the underlying autochthonous and allochthonous structural units or the basement. Evidence for a large fault extending into the bedrock of the Rhône valley is not given by the analysis of the investigated data on faults and striations from the SW edge of the Swiss Préalpes médianes.

Key words: Préalpes médianes plastiques, paleostress, earthquakes, strike-slip faults, N-S left-lateral, ESE-WNW right-lateral, fold and thrust development.

INTRODUCTION

New information on the present day stress field in the Alpine area of Europe have been made available through studies of earthquake focal mechanisms and in situ stress measurements (PAVONI 1977, 1987, 1989; NEUGEBAUER et al. 1980; BECKER et al. 1984; KLEIN & BARR 1987; ZOBACK et al. 1989; DEICHMANN & BAER 1990). Paleostress studies from the same area are based on the analyses of various types of stress indicators such as different sets of cracks, fractures and veins, or stylolites (PLESSMANN 1972; BERGERAT 1987a,b; SCHRADER 1988; TSCHANZ 1990). In the Préalpes fold-and-thrust belt however data on present day stress and paleostress are scarce (MOSAR 1988a; METTRAUX & MOSAR 1989; FRÖHLICH 1991).

Using paleostress determined from faults and striations, we will highlight the relationship between structural features in the Préalpes médianes and calculated stress orientations. Results on paleostress orientations associated with strike-slip tectonics and thrust related tectonics will be presented for the Préalpes médianes, the most important tectonic unit in the Préalpes. Similarities between the present day stress field as determined from recent earthquake focal mechanism data in the alpine foreland (Molasse basin and Jura mountains) and paleostress results from the Préalpes médianes will be discussed.

REGIONAL GEOLOGICAL SETTING

The Préalpes, as seen today, are formed by several klippen stretching along the nothern front of the Swiss and French Alps between the

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Mythen to the east of Luzern (Switzterland) to the *Klippe des Annes* near Annecy (France). The two major lobes are formed by the *French* or *Chablais Préalpes* south of lake Geneva and the *Swiss Préalpes* north of lake Geneva (*fig. 1*). Although located today to the NW of the Helvetic nappes and the crystalline basement of the Alps, the Préalpes have their paleogeographical origin further south on the meridional border of the former Tethyan margin of Europe and the northern margin of Africa (STAMPFLI & MARTHALER 1990; STAMPFLI et al. 1991). They have been detached from their basement and thrusted to NW over and beyond the Helvetic units to come to rest in their present day position at the southern edge of the Molasse basin south of the Jura mountains (MASSON 1976; ESCHER 1988).

The study area covers the leading part of the Swiss Préalpes mountain belt north-east of lake Geneva, more precisely the Préalpes médianes, the most important of several tectonic nappes forming the prealpine mountain belt (CARON 1973). No data on paleostress from faults are so far available from the lobe of the French Préalpes.

The Préalpes and Préalpes médianes

The Préalpes médianes are the most important of a whole stack of allochthonous structural and paleogeographical units (*fig. 1*). On top of the trailing part of the Préalpes médianes we find the Breccia Nappe. Resting on both the frontal part of the Préalpes médianes and the Breccia Nappe, is the Nappe Supérieure, which itself can be subdivided into four different units (Gets Nappe, Simme Nappe, Dranses Nappe and Gurnigel Nappe; CARON 1972). The Nappe Supérieure extends beyond the very frontal edge of the Préalpes médianes. In some places the Nappe Supérieure is overridden by the leading part of the Préalpes médianes due to late thrust movements (MOSAR 1991).

Classically the Préalpes médianes are subdivided into *Préalpes médianes plastiques* (also called *Médianes plastiques*), forming the frontal (NW) part of the nappe and *Préalpes médianes rigides* (also called *Médianes rigides*), forming the trailing (SE) part of the nappe (LUGEON & GAGNEBIN 1941). The *Médianes plastiques* consist in a succession of large scale fault related folds E-W oriented in the eastern part of the nappe to NNE-SSW and even N-S in the western part of the fold-and-thrust belt (JEANNET 1922; PLANCHEREL 1979; MÜLLER & PLANCHEREL 1982; METTRAUX & MOSAR 1989; MOSAR 1989, 1991). Folds and their genetically linked thrust-planes die out laterally and are relayed by other folds, thus forming *en échelon* structures, which can be viewed as transfer zones located where strike-slip faults are expected to develop. Such zones would allow for a constant overall slip displacement of the Médianes plastiques across them, but with changing displacement on individual thrusts associated with folds on the two sides of the *en échelon* zone (SNEDDEN 1989; TEARPOCK & BISCHKE 1991). The trailing part of the nappe, the *Médianes rigides*, is formed by one major, in some places one or two minor, imbricated thrust slices dipping to N/NW. Two major transport directions, N-S and NW-SE, towards the Alpine foreland have been determined. The large- and small-scale tectono-metamorphic events proceeded continuously and diachronically from S (trailing edge of the nappe) to N (frontal part of the nappe) and were complete before the Préalpes arrived on the future Helvetic nappes (MOSAR 1988b, 1989, 1991).

The Préalpes médianes are formed by limestones, dolomites, marls and shales ranging from Triassic to Tertiary in age (BAUD & SEPTFONTAINE 1980; TRÜMPY 1980; PLANCHEREL 1990). In the investigated Médianes plastiques the stratigraphic sequence ranges from interlayered shales and dolomites of the Upper Triassic to the Tertiary flysch. Interlayered marls and limestones are frequent in the Middle Jurassic and Lower Cretaceous. The Upper Jurassic is characterized by an important 20-200 metre thick competent limestone horizon outcropping almost throughout all the Préalpes médianes (HEINZ & ISENSCHMID 1988) and thus plays an important role in the structural development of folds and thrusts (PLANCHEREL 1979).

STRESS DETERMINATION FROM EARTHQUAKES AND FAULTS

The kinematic history of a single fault is defined by striations on its fault surface. For a population of faults the observations on fault

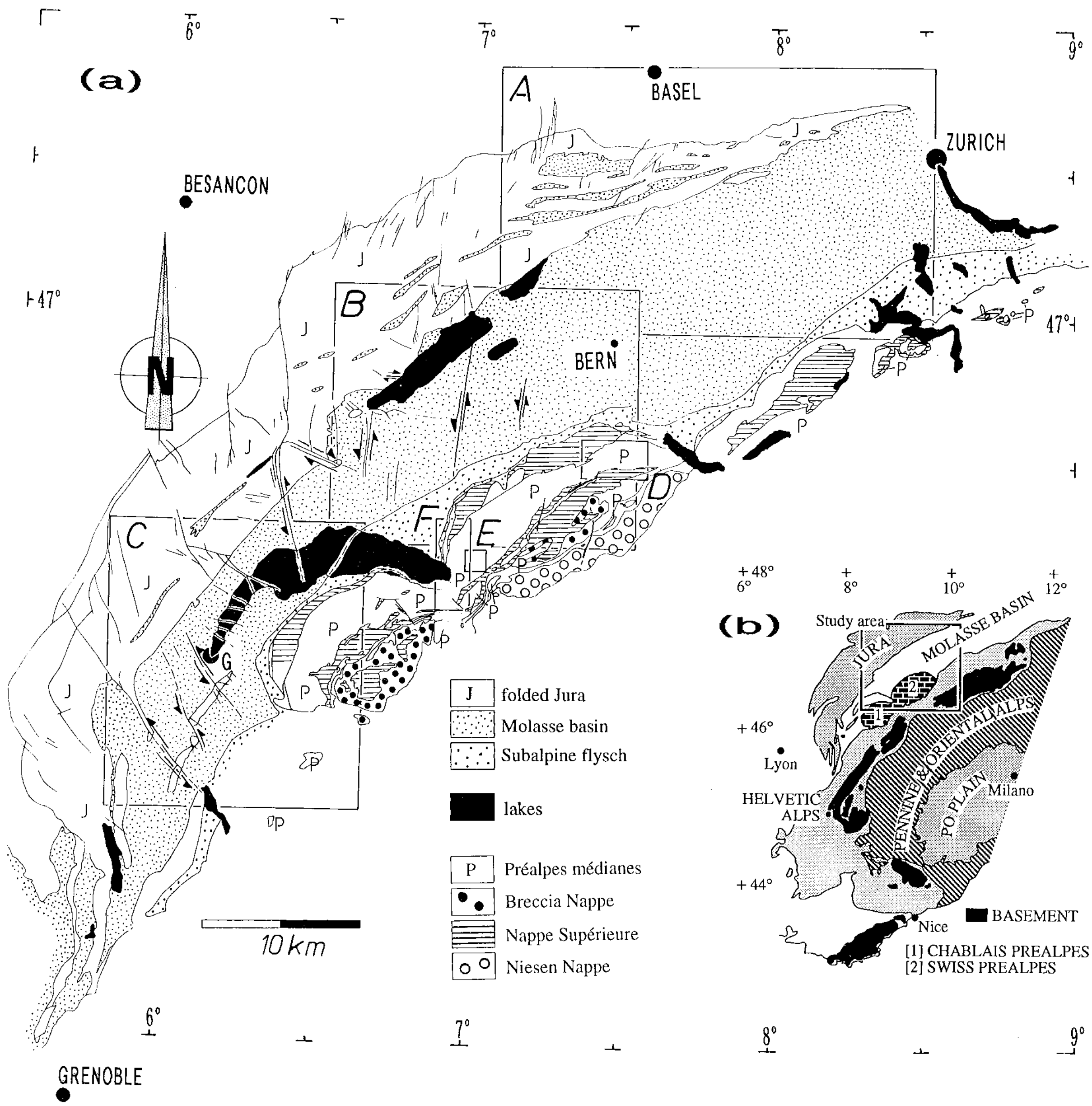


Fig. 1 - (a) Simplified structural map of the Préalpes and their N and NW Alpine foreland formed by the Molasse basin and the Jura mountain belt. Regions highlighted by dashed lines refer to investigated areas: A = data from DEICHMANN (1990); B = data from FRÖHLICH (1991); C = data from SAMBETH & PAVONI (1988); D = Weissenburgbad strike-slip zone near Boltigen (BOREL 1991); E = strike-slip and thrust system of the Hongrin river area; F = strike-slip zone along the NE Rhône river valley near Montreux. (b) Simplified structural and geological map of the alpine arc in western and central Europe. Major subdivisions are shown in a longitude-latitude grid.

plane orientation and the associated striation allow the determination of the three principal stress axes and the associated uncertainty. The technique applied to our field data from the Préalpes, is a graphical method applying statistics to half space compression (P) and/or tension (T) dihedra, as defined by faults and their respective striation (ARTHAUD 1969; ANGELIER 1975, 1984, 1989, 1990; ANGELIER & MECHLER 1977; LISLE 1987, 1988; PFIFFNER & BURKHARD 1987; MARRET & ALLMENDINGER 1990). The same technique can also be applied to solutions of focal mechanisms for earthquakes.

For our study we used the software package

«Fault-kinematics» developed by ALLMENDINGER et al. (1989) based on the right dihedra method from ANGELIER & MECHLER (1977). The kinematic analyses of the fractures in terms of stress, supposes that the movement, which is assumed to be by rigid block motion indicated by striae, occurs parallel to the direction of resolved shear stress on a newly formed or preexisting fault. Furthermore the deviatoric stress is assumed to be uniform over the local area of investigation. This last assumption may be invalid in some cases and will be discussed later.

PALEOSTRESS RESULTS FROM THE PRÉALPES MÉDIANES

Fault-striae populations have been sampled in different localities throughout the Préalpes médianes from several lithologies and well known tectonic environments. We tried to measure as many faults, with as large a scatter in orientations, as possible. In all cases all data have been collected from areas of small geographical extent (no more than 500 m in diameter). In most cases sampling localities are associated with a single well known and well developed tectonic feature. It was not possible to determine relative age relationship amongst different faults in the investigated localities from the Préalpes médianes (no obvious cross-cutting relations could be determined). Several sites have been given special attention due to their specific structural setting. First, we will take a close look at the right lateral strike-slip fault of *Weissenburgbad* (near Boltigen, *fig. 1a-D*) in the Médianes plastiques (PLANCHEREL 1979; BOREL 1991). A second example deals with the combined strike-slip and thrust tectonics SW of Château-d'Oex in the *Dent de Corjon* syncline and the *Tinière-Dorena* anticline area (*fig. 1a-E*, PLANCHEREL & WEIDMANN 1972; METTRAUX & MOSAR 1989). A third set of results comes from the western edge of the prealpine arc in Switzerland, along the NE side of the Rhône river near Montreux (*fig. 1a-F*, METTRAUX & MOSAR 1989).

(i) The right lateral strike-slip zone near Weissenburgbad, northeast of Boltigen (*fig. 2*) has been known for some time (BIERI 1925; PLANCHEREL 1979), but only recently have detailed investigations focused on the strike-slip nature of this fault (BOREL 1991). The strike-slip zone, 6 km long, as can be seen from field evidence, cross-cuts the existing anticlinal and synclinal structures and offsets them by 500-800 m. Its continuation to the east is difficult to trace but possibly extends into the *«Walper Schuppenzone»* (BIERI 1925; NICOL 1956). This zone forms a W-E trending succession of steeply dipping, horse shaped thrust structures which most likely suffered a late strike-slip movement (MOSAR 1988a, 1991). Westward the strike-slip zone enters a kilometric anticlinal line, which appears in this region as a double thrust.

The data have been collected near the strike-slip zone (*fig. 2-A*) as well as at some distance to the SW in the vicinity of a set of imbricated thrust structures. Results near the strike-slip zone in the Upper Cretaceous-Eocene, the Lower Cretaceous, the Upper Jurassic and the Middle Jurassic show well defined directions for the resulting compression and tension (*fig. 3*), in spite of the variations between lithologies: from massive limestones developing kilometric folds to marls characterized by isoclinal metric folds. The tension axes have constant subhorizontal ENE-WSW to NE-SW orientations in all four fault sets investigated. Compression is oriented NW-SE to NNW-SSE. The density stereograms clearly indicate a strike-slip tectonic regime. Two possible orientations for major faults or fault zones are given: one N-S with a sinistral movement and one N110E with a dextral displacement. As known from field evidence the second fault system has been predominant (see also BOREL 1991). The coherence of the results clearly shows that the measured faults are linked to the development of a right lateral strike-slip zone.

(ii) A second region of investigation extends between Montbovon to the N and lake Hongrin to the S (*fig. 4*), mainly in the vicinity of the Hongrin river valley. The main structural features that characterize this area are, from NW to SE: 1) the Sarine valley or Intyamon syncline (*fig. 4-[a]*) with its second order folds on the southern flank and a series of thrusts NW of the Dent de Corjon (PLANCHEREL 1979); 2) a tight anticline between the Intyamon and the Dent de Corjon synclines that shows a top-to-the-NW movement along a thrust surface in its core (*fig. 4-[b]*); 3) the Dent de Corjon syncline

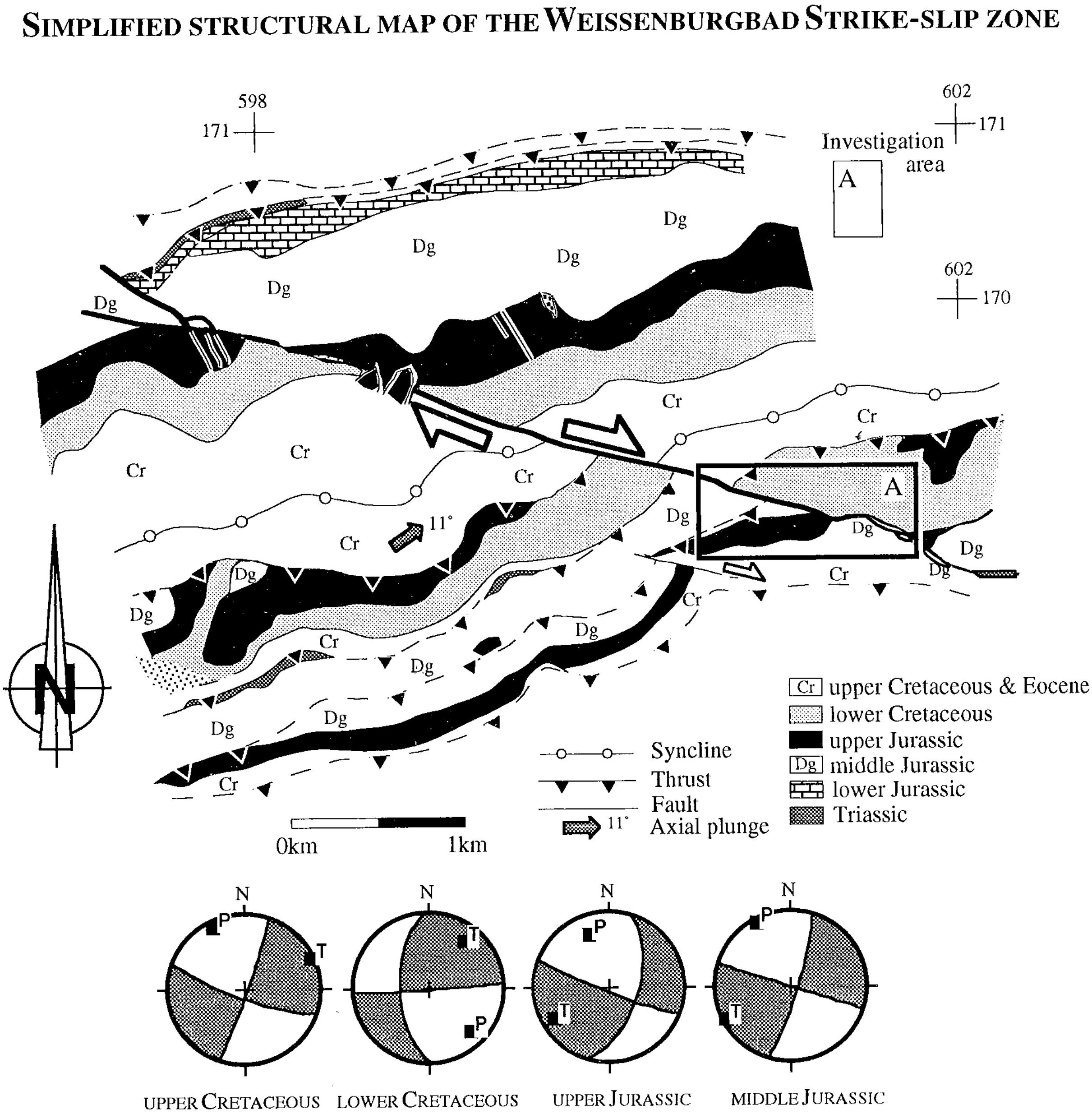


Fig. 2 - Simplified geological map of the Weissenburgbad strike-slip zone and its lateral extension into the Walper Schuppenzone. Displacement is right lateral along the major faults oriented N110E on the Weissenburgbad strike-slip zone and E-W along the Walper Schuppenzone. Stereonets (equal area, lower hemisphere) are simplified fault-plane solutions with compression (P) and tension (T) axes.

(*fig. 4*-[*c*]), which is the extension to the NE of the Rochers de Naye syncline (*fig. 4*-[*d*]). This structure forms a rather large syncline with a thrust in its northern limb. The whole appears to be thrust toward the NW; 4) the complex Dorena-Tinière anticlines (*fig. 4*-[*e,f*]). Near the Hongrin river both these anticlines end with a periclinal structure and form an *en échelon* relay structure. They are associated with thrust surfaces that develop in the fold core.

Data from the Dogger of the SW Dorena anticlinal core and limb (near Col des Gaules) indicate stress orientations consistent with a reverse movement on a thrust surface with a

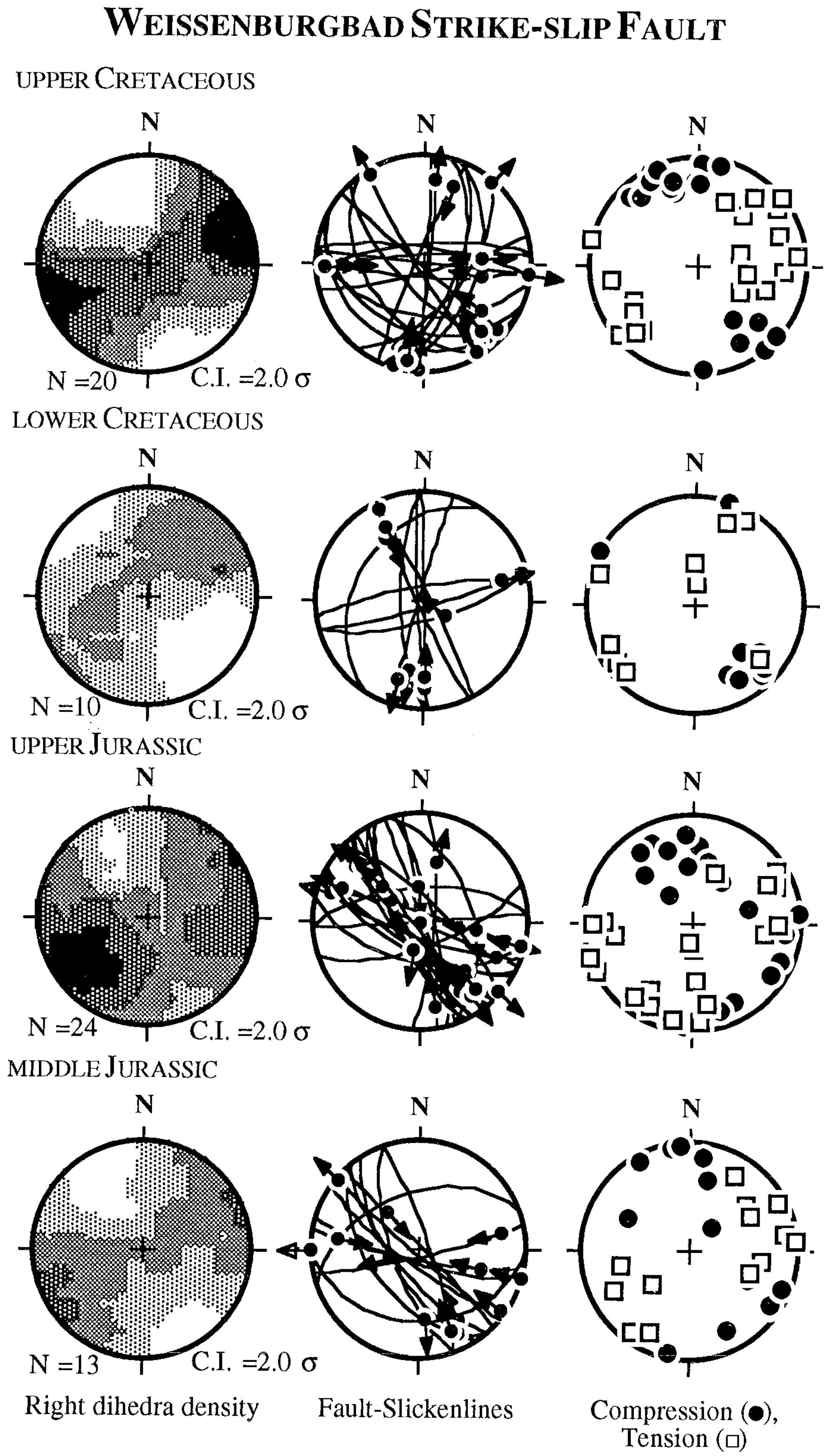


Fig. 3 - Stereonet projections of original fault-striation data, compression (P) and tension (T) axes determined from right dihedra and density contours for best T axes from the kinematic right dihedra analyses for the Weissenburgbad area. Arrows along fault plane great circles indicate movement of upper block; contours have been calculated using the Kamb method in the Fault Kinematics program by ALLMENDINGER et al. (1989) (stereonets are equal area, lower hemisphere).

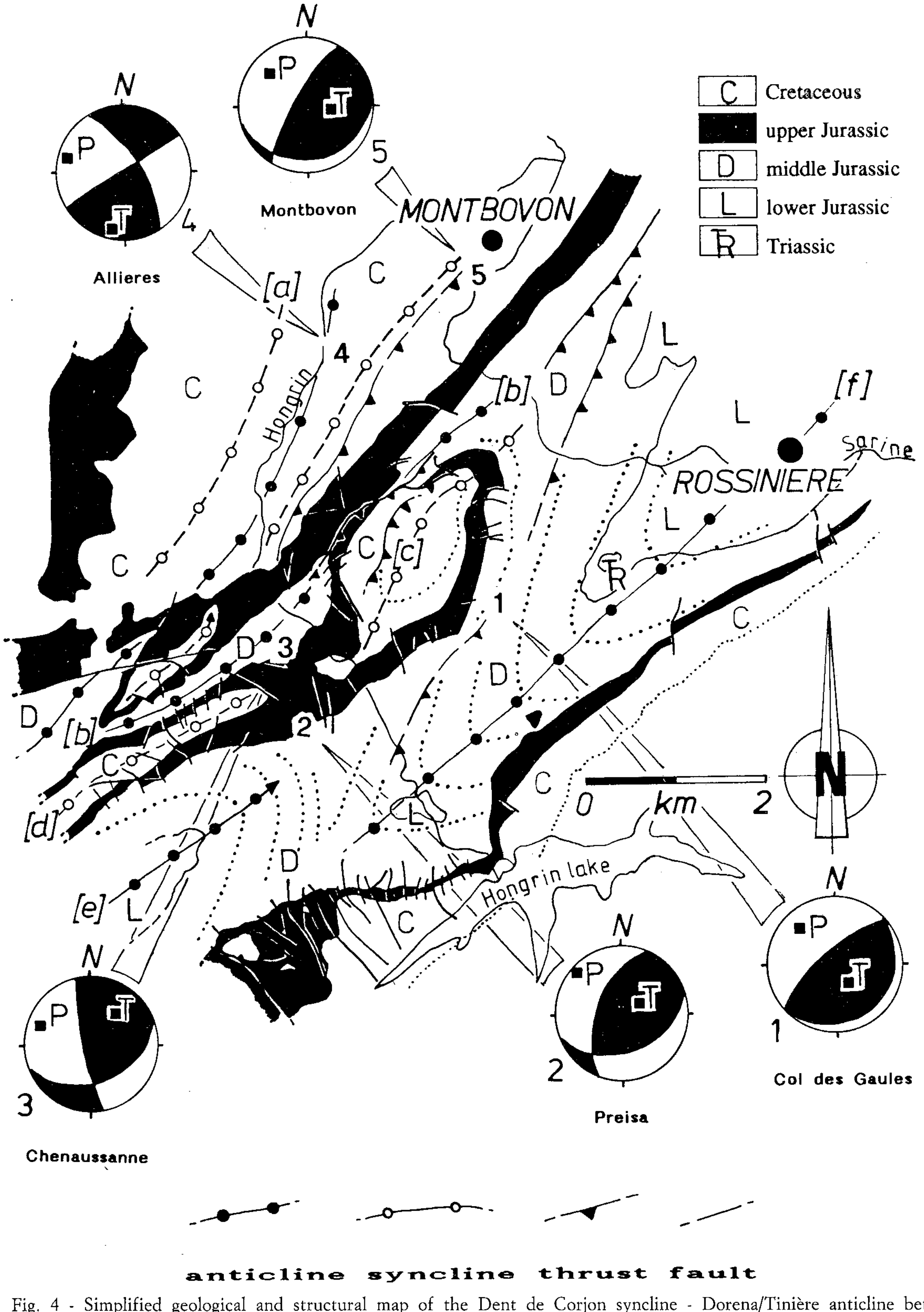


Fig. 4 - Simplified geological and structural map of the Dent de Corjon syncline - Dorena/Tinière anticline between Montbovon and Rossinière. The main structures (anticlines, synclines, faults and thrusts) are shown as well as an outline of the structural contours (based on bedding orientation data) of the periclinal closures of the Dorena and Tinière anticlines forming an en echélon structure in the Hongrin river valley. (Map compiled from own data and maps by BADOUX 1965 and PLANCHEREL 1979). Stereonets as in *fig. 2*.

NE-SW direction, dipping either gently to SE or steeply to the NW (the latter case would represent a backthrust with respect to the general transport direction to the N-NW *figs. 4,5*). Data from the Upper Jurassic at Preisa (*figs. 4-2, 5-2*) in the Hongrin river valley along the southern limb of the Dent de Corjon syncline show a mixed tectonic regime. Sinistral displacement occurs along steep faults oriented N10-20E, while thrusting occurs on surfaces dipping to the SE and oriented NE-SW. On the nothern limb of the same syncline (*figs. 4-3, 5-3*), also in the Upper Jurassic, fault sets indicate yet another mixed tectonic environment. Left lateral strike-slip occurs along subvertical faults oriented N 350 E and reverse movement is dominant on thrust surfaces oriented NE-SW dipping towards the NW. Data from the southern part of the Intyamon syncline along the Hongrin river (near Allières, *figs. 4-4, 5-4*) indicate a strike-slip regime with NW-SE and NE-SW oriented faults with dextral respectively sinistral movements. Closer to Montbovon in the vicinity of a NE-SW striking thrust we observe a dominant thrust regime in rocks of Upper Cretaceous (*figs. 4-5, 5-5*). Overall in the study area the compression axes have a WNW-ESE to NW-SE subhorizontal orientation, while the tension axes vary in plunge around a general NE-SW direction.

(iii) The third area investigated extends from SE to NW along the NE bank of Rhône river near Montreux (*fig. 6*). A succession of several major fault related folds forming the western termination of the Swiss Préalpes médianes can be observed (TRÜMPY 1960; BADOUX 1965; METTRAUX & MOSAR 1989). To the north of Montreux a succession of three imbricated thrust slices mainly with Lower Jurassic and Triassic, forms the very frontal part of the Préalpes médianes fold-and-thrust belt. They are underlain to the W and NW by the Gurnigel nappe (which forms one out of four units of the Nappe Supérieure), Ultrahelvetic slices and the Subalpine flysch and molasse. Thrust surfaces (*fig. 6*) dip to the east and have a NNE-SSW to N-S orientation with a top-to-the-west movement. To the south follows a succession of anticlines and synclines. The most prominent are from north to south: the Rochers de Naye syncline (*fig. 6-a*), the Tinière anticline (*fig. 6-b*; PLANCHEREL & WEIDEMANN 1972), a complex syncline including remnants of the Nappe Supérieures (*fig. 6-c*), the Tours d'Aï anticline (*fig. 6-d*) and the Leysin syncline (*fig. 6-e*). All these structures are affected by a large number of faults at a high angle with the NE-SW fold axis direction (*fig. 6*). It was possible to show that most of those structures display clear evidence of strike-slip diplacements. Thus along important fault planes in the Montreux area it was possible to document large groove marks indicating strike-slip movements. These faults near Montreux (*figs. 6-7*) have a WNW-ESE orientation and most likely a right-lateral displacement as can be seen in similar structures mapped by PLANCHEREL & WEIDMANN (1973) near Glion, SE of Montreux. Measurements of faults have been made in the quarries near Roche in the Upper Jurassic and the Upper Cretaceous, near Villeneuve in the Lower Jurassic, in the vicinity of Corbeyrier in the Triassic and Upper Jurassic, as well as in two of the imbricated thrusts north of Montreux in the Lower Jurassic (see also METTRAUX & MOSAR 1989).

All results from fault analyses from the Rhône valley show the distinct pattern of a strike-slip tectonic regime with well developed poles of subhorizontal compression and tension (*fig. 7*). The tension axes are quite consistent, being closely scattered around the NE-SW direction. Results from field observations and fault analyses show that near Corbeyrier (*fig. 6-6*) and in the Upper Jurassic near Roche (*fig. 6-5*) NNW-SSE oriented sinistral faults are dominating. In the Upper Cretaceous in Roche on the other hand it is the right lateral NW-SE trending fault set that is dominant. Near Arvel a NNW-SSE dominating sinistral fault set prevails.

Results from the frontal thrust imbrications are less conclusive, but from field data it appears that a dominating NNW-SSE to NW-SE left-lateral fault set exists (*figs. 6-1, 6-2*).

PRESENT DAY AND PALEO-STRESS IN THE W AND NW ALPINE FORELAND

Investigations on paleostress orientations in the vicinity of the north-western Alpine foreland have been done using a variety of stress indicators such as: (i) fault-striae couples (BERGERAT 1987a, b; LARROQUE & LAURENT 1988;

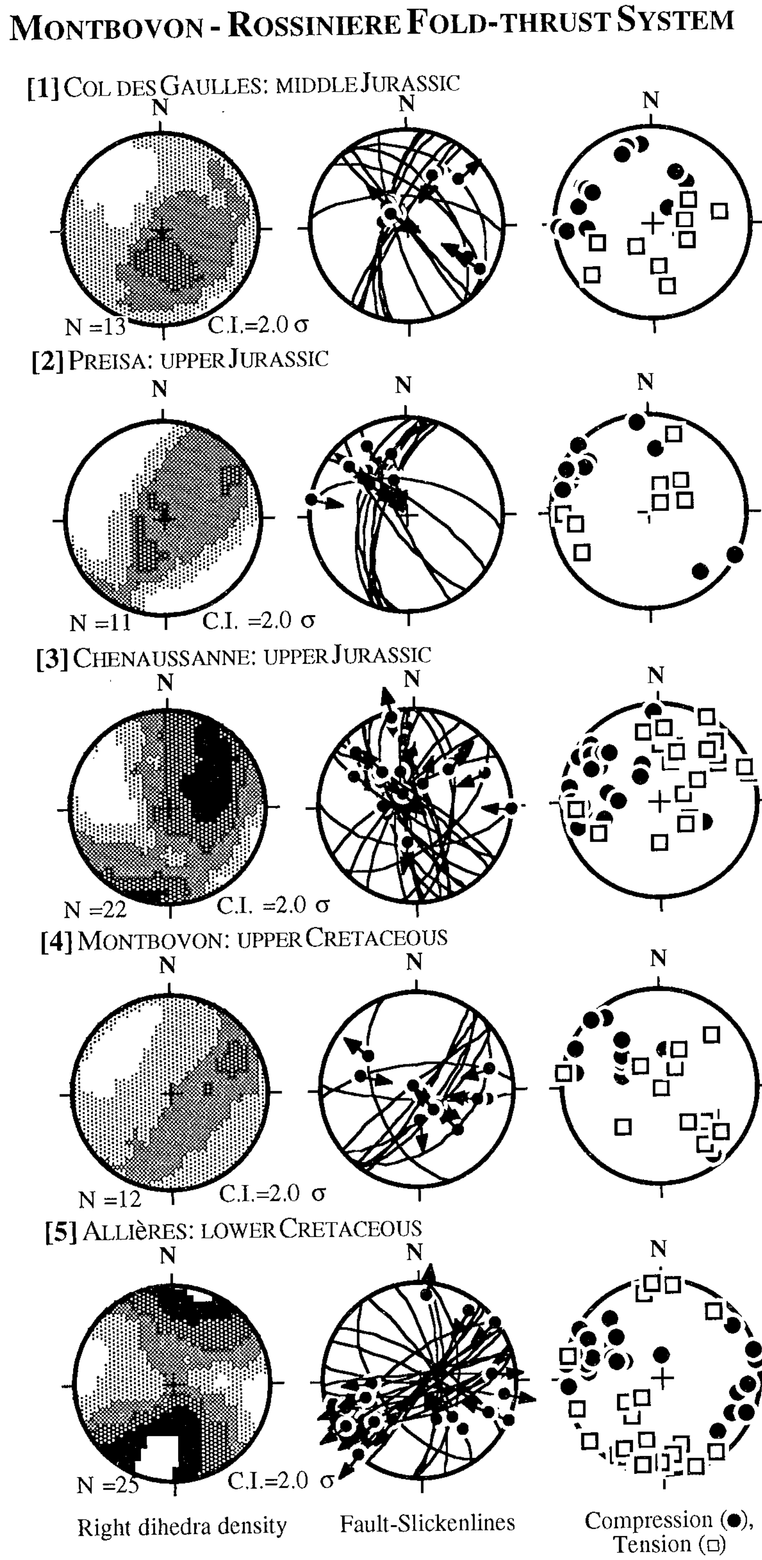


Fig. 5 - Stereonet projections of original fault striation data, compression (P) and tension (T) axes determined from right dihedra and density contours for best T axis from the kinematic right dihedra analysis for the Hongrin river area. Arrows along fault plane great circles indicate movement of upper block; contours have been calculated using the Kamb method in the Fault Kinematics program by ALLMENDINGER et al. (1989) (stereonets are equal area, lower hemisphere).

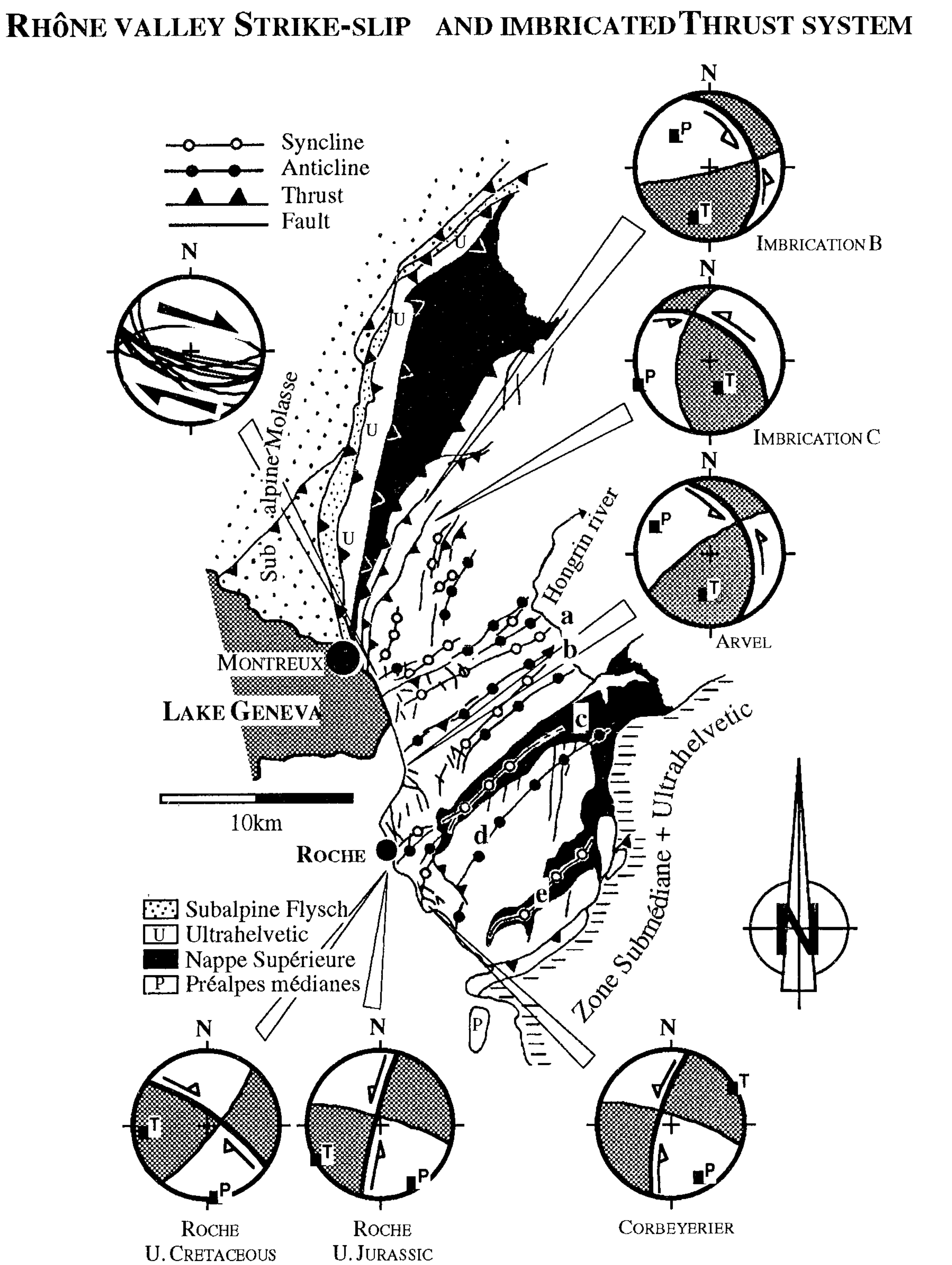


Fig. 6 - Simplified map of the western termination of the Swiss Préalpes médianes NE of Lake Geneva. Frontal imbricated tectonic slices are in front and below of the Médianes plastiques to the W and NW. Stereonets as in *fig. 2*.

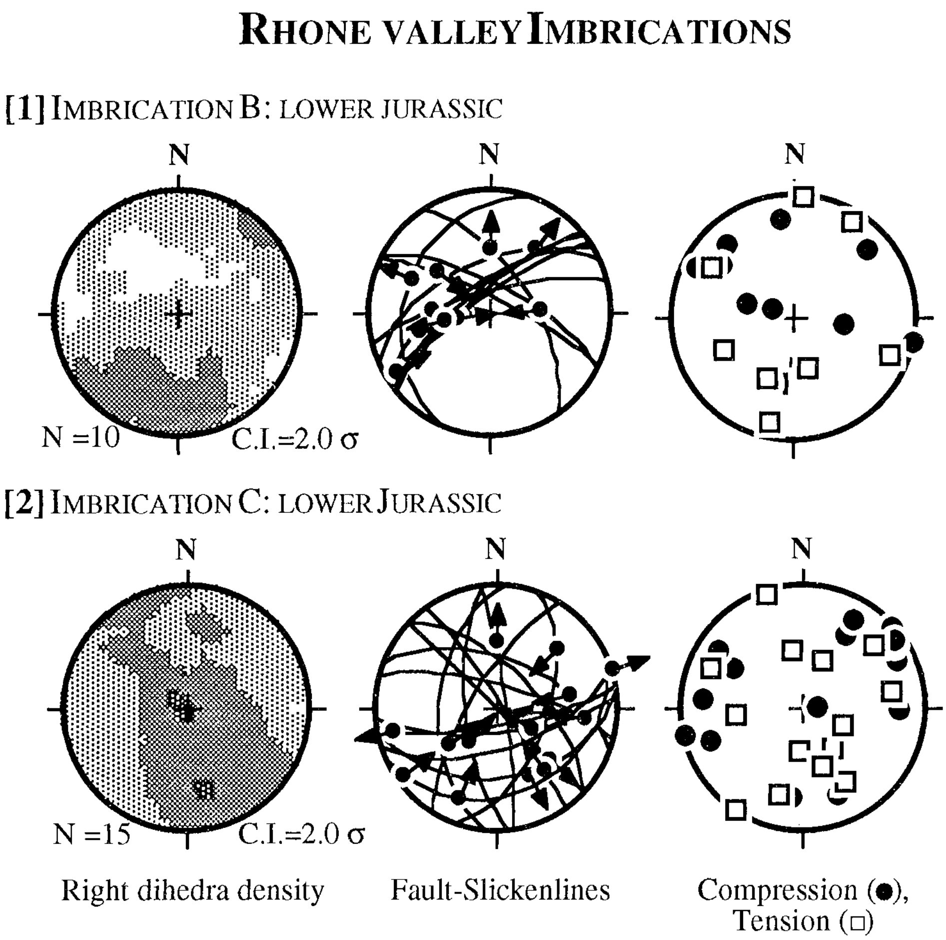


Fig. 7 - Stereonet projections of original fault-striation data, compression (P) and tension (T) axes determined from right dihedra and density contours for best T axes from the kinematic right dihedra analysis for the Rhône valley area. Arrows along fault plane great circles indicate movement of upper block; contours have been calculated using the Kamb method in the Fault Kinematics program by ALLMENDINGER et al. (1989) (stereonets are equal area, lower hemisphere).

VUILLEMIN & BERGERAT 1987), (ii) stylolites (PLESSMANN 1972; TSCHANZ 1990; SCHAER et al. 1990) and (iii) pressure solution on pebbles (SCHRADER 1988). In situ stress measurements, earhquake focal mechanism studies and geodetic investigation have been given considerable attention in recent years (AHORNER 1975; PAVONI 1977, 1987; BECKER 1989).

Results from this research show that the most consistent stress orientation throughout the NW Alpine foreland is the NE-SW trending horizontal tension axis σ3. The general NW-SE trending stress axis is either σ1 or σ2 depending on the local movements, structural features and stress gradients (DEICHMANN 1990). The NE-SW extension appears to be associated mainly with strike-slip faults. It is suggested that these movements are no older than 10-15 Ma (BECKER 1989). A closer look reveals that the maximum horizontal stress trends NNW-SSE in northwest Switzerland, NW-SE in central Switzerland and ESE-WNW south of lake Geneva (PAVONI 1987; SAMBETH & PAVONI 1988; BECKER 1989; DEICHMANN 1990; FRÖHLICH 1991). We have analyzed compression and tension axes from earthquake focal mechanism solutions with the right dihedra method in three areas in the Alpine (and prealpine) foreland: (i) the larger area around the NE termination of the Jura (*fig. 1a-A;* data from DEICHMANN 1990), (ii) an area between the southern Jura north of lake Neuchâtel and

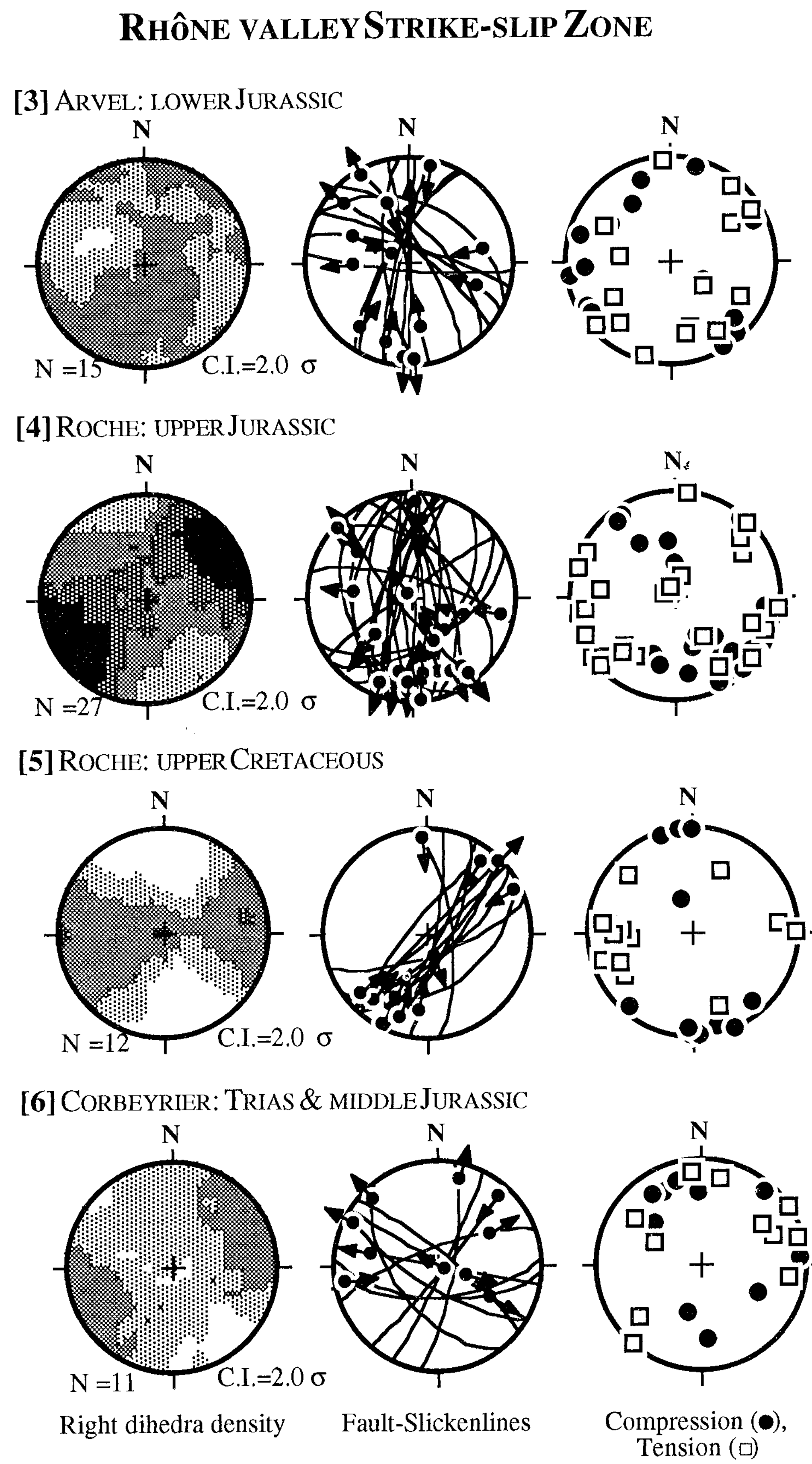

RHÔNE VALLEY STRIKE-SLIP ZONE
[3] ARVEL: LOWER JURASSIC
N
N
N
N =15
C.I.=2.0 σ
[4] ROCHE: UPPER JURASSIC
N
N
N
N =27
C.I.=2.0 σ
[5] ROCHE: UPPER CRETACEOUS
N
N
N
N =12
C.I.=2.0 σ
[6] CORBEYRIER: TRIAS & MIDDLE JURASSIC
N
N
N
N =11
C.I.=2.0 σ
Right dihedra density
Fault-Slickenlines
Compression (●),
Tension (□)

Fig. 7

the frontal Préalpes to the south (*fig. 1a-B;* data from FRÖHLICH 1991) and (iii) a region comprising the Jura and the Molasse west and south of Geneva (*fig. 1a-C;* data from SAMBETH & PAVONI 1988).

It is obvious from single earthquake analyses associated with fault structures such as the Vuache strike-slip fault (BLONDEL et al. 1988) that stress orientations are dependent on local structural heterogeneities (see also MOUNT & SUPPE 1987). Regional stress orientations on the scale of the Molasse basin and Jura, however, can be determined if large numbers of stress axes are integrated in a statistical analysis.

DISCUSSION

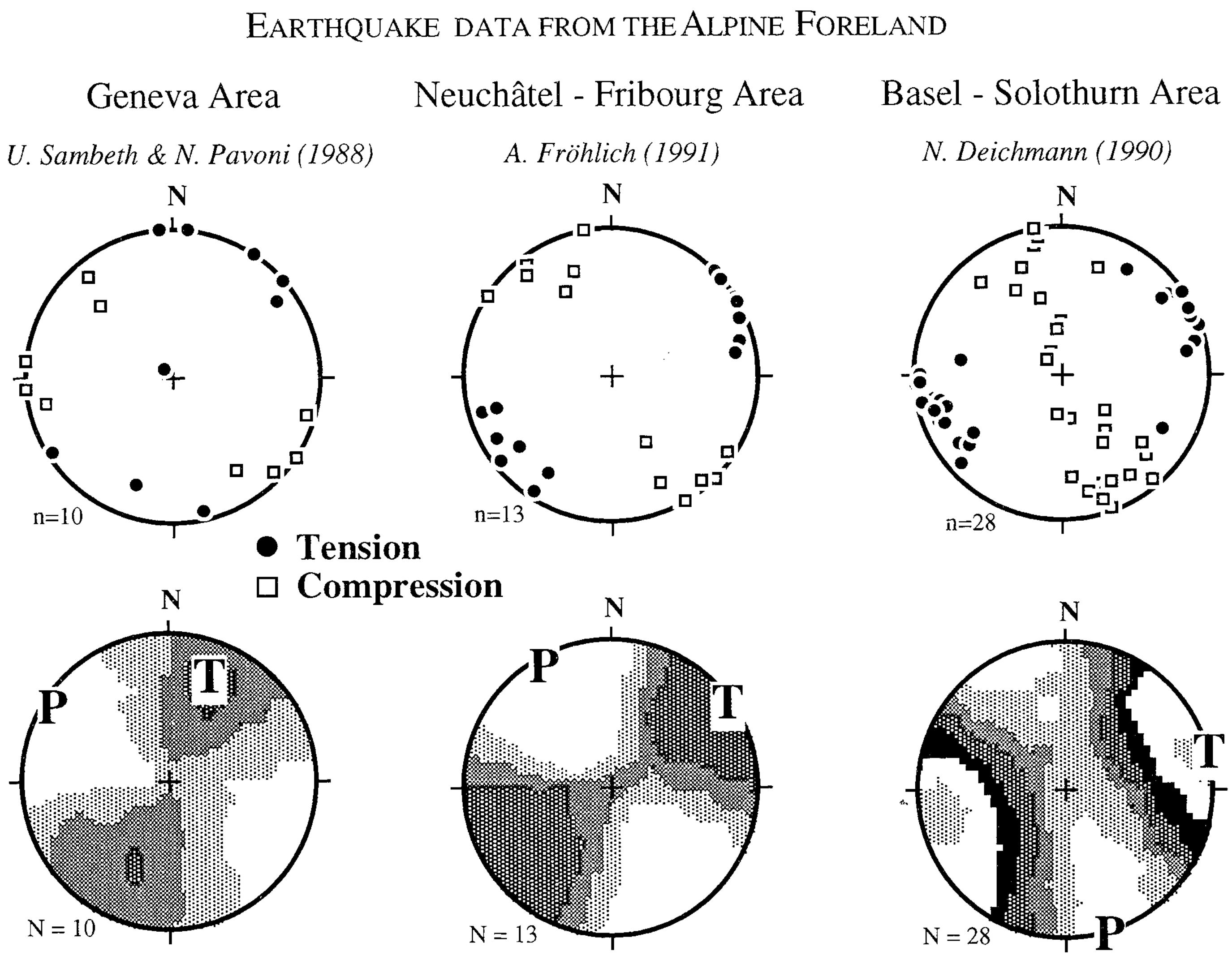
Field studies allow observation of fault plane orientations and displacement directions (striation). From these data it is possible to estimate strain values affecting the fault rock. As displacements observed in the Préalpes médianes are small compared to fault extension, it can be argued that the small increment of deformation can be compared with the stress that generated these faults (see PFIFFNER & BURKHARD 1987; ANGELIER 1990).

The relative age of analyzed faults was impossible to determine in the field. The great consistency in results from the right dihedra method however suggests that: (i) the stress can be considered uniform over the areas of investigation and (ii) the investigated data sets belong to one single tectonic event (with a distinct stress field), or alternatively that the fault-striae data belong to different tectonic events, but with coaxial stress fields. In the latter case, the faults would thus be preexisting features that have been active during several periods of the fault and fold development. It cannot be excluded, however, that the faults developed under older and different stress orientations but reactivation generated the striae measured in this study. This could, however, not be documented from field observations in the Préalpes médianes.

From field observation and as a result from this study it appears that some faults are associated with the development of thrusts that are linked to the formation of folds (MOSAR 1991). Other fault sets are associated with strike-slip tectonics. Different sets highlight different main shear directions: NNE-SSW sinistral; NNW-SSE sinistral or WNW-ESE dextral. All these sets are coherent with a dominant N-S left-lateral shear zone, as seen on the NW slope

TABLE 1 - *Results from Fault Kinematic Analyses (ALLMENDINGER et al., 1989) on measured fault-striae data from the Préalpes médianes. nbr = number of measured faults; P axis and T axis are given in azimuth and dip of calculated axes; P% and T% = percentages of faults and striae consistant with the calculated compression (P) or tension (T) axis.*

Fault kinematic Analyses (using ALLMENDINGER et al. 1989)							
	Locality	Period	nbr	P axis	T axis	P %	T %
(i)	Weissenburgbad	upper Cretaceous	20	157/5	243/17	100	100
	Weissenburgbad	lower Cretaceous	10	153/17	68/33	90	100
	Weissenburgbad	upper Jurassic	24	329/28	225/30	87	87
	Weissenburgbad	middle Jurassic	13	323/38	247/5	100	100
(ii)	Col de Chaude	middle Jurassic	21	225/76	20/10	95	100
(iii)	Col des Gaules	middle Jurassic	13	326/53	153/43	100	92
(iv)	Chenaussanne	upper Jurassic	22	90/59	196/10	90	90
(v)	Preisa	upper Jurassic	11	146/11	198/58	100	100
(vi)	Charmey-Jaun	lower Cretaceous	11	146/53	243/17	90	90
(vii)	Allières	lower Cretaceous	25	113/05	188/13	88	96
(viii)	Montbovon	upper Cretaceous	12	297/43	90/59	91	91
(ix)	Ciernes	lower Jurassic	15	323/36	214/11	100	86
(x)	Petere anticline	Triassic	13	117/67	90/14	84	92
(xi)	Imbrication B	lower Jurassic	10	342/56	172/13	90	80
(xii)	Imbrication C	lower Jurassic	15	90/14	169/36	80	80
(xiii)	Roche	upper Jurassic	27	143/38	225/30	81	81
	Roche	upper Cretaceous	12	166/47	90/00	91	91
(xv)	Arvel	lower Jurassic	15	304/53	191/36	86	73
(xvii)	Corbeyrier	Triassic & up. Jura	11	90/80	230/3	90	81



(Counting interval. = 2.0 s, equal area, lower hemisphere stereographic projections)

Fig. 8 - Data from earthquake focal mechanism solutions. Compression and tension axis for the three investigated areas shown (*fig. 2*). Density stereonets from tensional faultkinematic analysis on P and T data (equal area projections, lower hemisphere). Analyses have been made in tension mode and all three areas show a maximum of 100% consistency.

of the Rhône valley near Montreux or along the Hongrin river.

The three investigated areas show that the dominant strike-slip zone changes orientation to extend into thrust surfaces parallel to the regional fold axis. We propose that they form as tear faults, similar to those observed in the eastern Médianes rigides in a fault-bend fold and imbrication environment (MOSAR 1991). As such they are associated with transfer zones where displacement is variably distributed in single fault-fold structures across the transfer zone, but remains constant overall. This can best be seen along the Hongrin river (SW of Château-d'Oex) where the tear fault zone is N-S sinistral, but also near Weissenburgbad where the tear fault trends N110E with a dextral movement.

Comparison of fault and stress orientations from the Jura and Molasse with those from the Préalpes médianes shows striking similarities. Results from the right dihedra stress analysis on all data from: (i) the Rhône valley and (ii) from the Weissenburgbad strike-slip fault (*fig. 9*) are comparable in all respects with results on earthquake data from the Jura and Molasse north of the Swiss Préalpes (*fig. 8*). In both cases we have a strike-slip regime with sinistral movements along a N-S trending fault and dextral displacements along E-W trending faults. This might lead to the conclusion that all these fault systems are related to the same stress field and the same tectonic event. In that case the fold and thrust development in the Préalpes médianes which is associated with the fault development discussed herein, would be contemporaneous with the fault movements in the Molasse basin and in the Jura, that is after its actual emplacement in front of the Helvetic nappes. This hypothesis, developed by PLANCHEREL (1979), implies the presence of deep strike-slip faults rooting in the basement and affecting all the Alpine foreland, the Préalpes klippen included. It is, however, difficult to find conclusive evidence for such strike-slip faults cross-cutting all the Préalpes nappes and its Molasse substratum. Thus a second hypothesis, proposed by MOSAR (1991), suggests that the fold development linked with the fault systems analyzed here, has occurred before the emplacement of the Préalpes klippen in their present position. Most fault systems would thus be transported features. We could then possibly be in presence of two different but coaxial tectonic events. It can be speculated that the observed faults have been subjected to several successive stress events during which they have been reactivated repeatedly, the most recent being still active, as seen from earthquake data.

CONCLUSIONS

(i) The fault-striation sets analyzed here show a remarkably high percentage of mutually

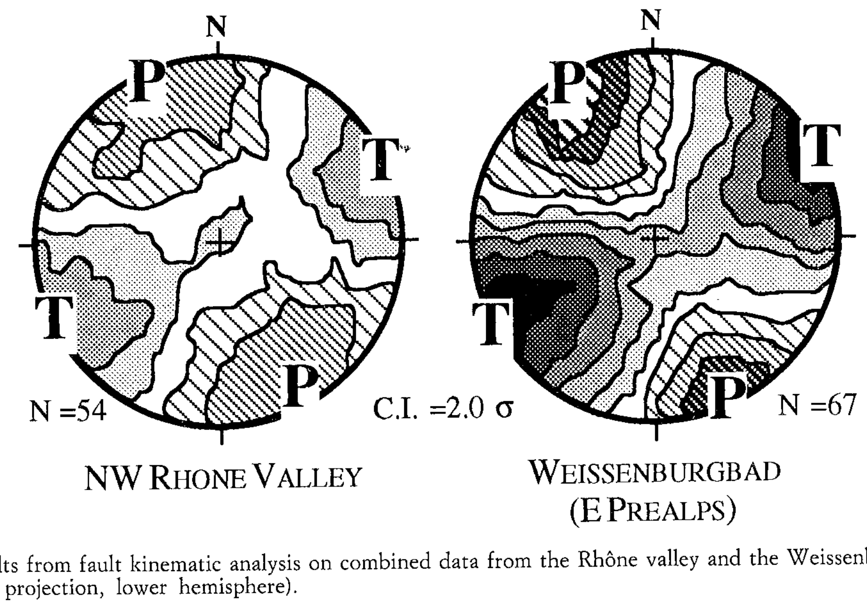


Fig. 9 - Results from fault kinematic analysis on combined data from the Rhône valley and the Weissenburgbad strike-slip zone (equal area projection, lower hemisphere).

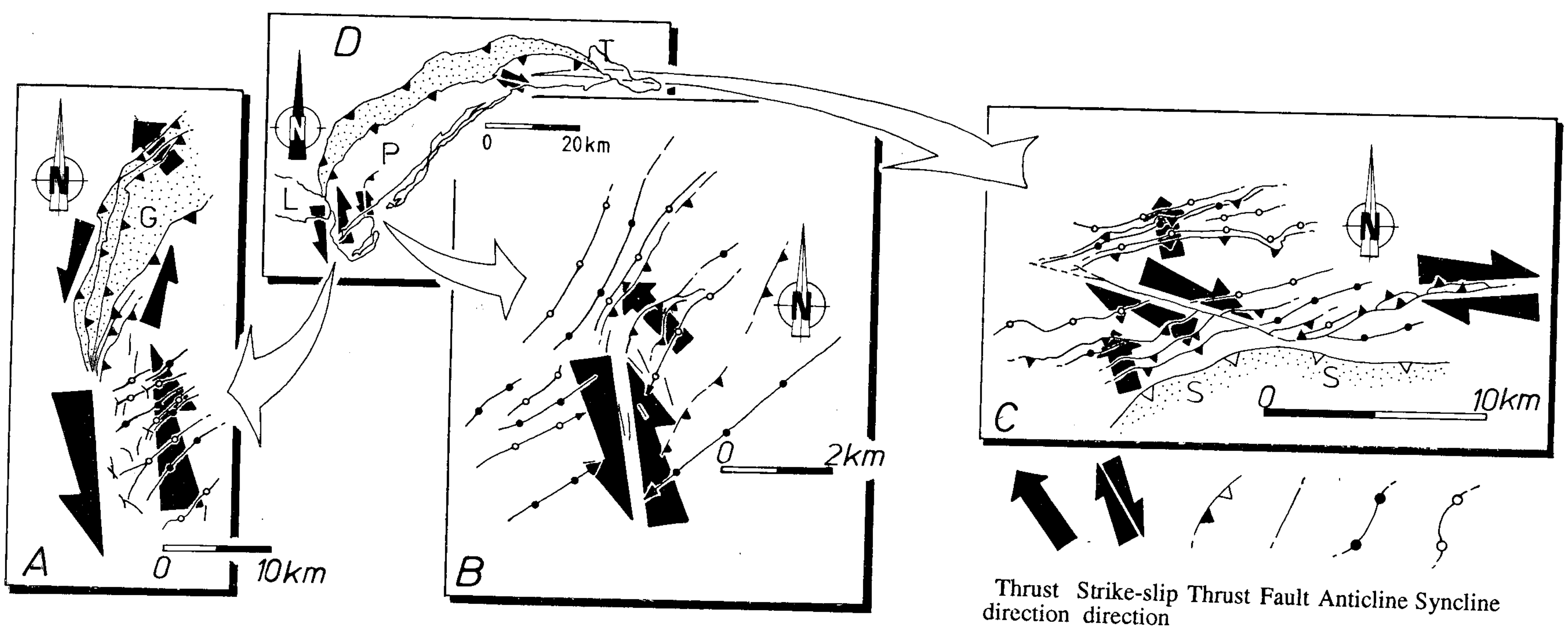


Fig. 10 - Simplified models integrating results from fault-striation analyses and fault-fold development in the Swiss Préalpes médianes. (A) Rhône valley left-lateral strike-slip fault zone. To the N the fault extends into a set of thrusts showing combined thrust and left-lateral strike-slip movements. The extension to the S remains unclear, because the Préalpes do not extend any further south. G = Gurnigel nappe (one of four units of Nappe Supérieure). (B) Montbovon-Hongrin river area SW of Château-d'Oex. The N-S oriented left-lateral strike-slip system terminates to the S into an *en échelon* relay structure formed by two adjacent anticlines (Tinière anticline to the SW plunging to the NE and Dorena anticline to the NE plunging to the SW). To the N the strike-slip zone changes orientation and extends into a system of several thrusts with top-to-the-NW movements. (C) Right-lateral strike-slip zone of Weissenburgbad in the eastern Préalpes médianes. The N110E oriented fault is assumed to be contemporaneous with the fault and thrust development or slightly postdate this event. It probably extends to the E into an E-W oriented fault system along which right lateral movements have been documented (Mosar 1988a). To the W the strike-slip fault runs into a fold and thrust system. S = Simme nappe (one of four units of the Nappe Supérieure). (D) Simplified sketch of the Préalpes médianes plastiques (P) and its underlying frontal units (stippled) showing the location of the investigated areas and structures. L = lake Geneva; T = lake Thun.

consistent fault movements. In most cases the maximum percentages of compatible faults, as well from tension as from compression analyses, are higher than 73% with a mean value of 89% for results from the tension analyses and 91% for the compression analyses. These results justify the use of the applied techniques to compute paleostress tensors from fault-striae sets. It also is an indication that we are dealing with fault sets associated with the same event or at least with two or several coaxial tectonic events since otherwise a larger number of incompatible fault sets should be observed. This is reinforced by the fact that all data have been sampled in small areas in the vicinity of a well defined structural feature such as a thrust or a fault.

(ii) Two types of tectonic regimes are predominant amongst the investigated fault systems in the Swiss Préalpes médianes. The first is a strike-slip environment linked to large vertical fault zones. Movements associated with the more or less N-S trending faults are left-lateral (see also PLANCHEREL 1976, 1979), whereas they are right-lateral along N110E oriented faults. The second type of structural environment is a NE-SW to NNE-SSW (in some places almost N-S) trending thrust system associated with fold development and with a top-to-the-NW movement.

(iii) It can be shown that the fault development appears to be contemporaneous with the fault-fold development. It cannot be ruled out that some of the faults, as those observed in the Rhône valley or along the Weissenburgbad strike-slip zone, may reflect a late stage in the development of the major fold structures but still related to the general emplacement tectonics of the allochthonous Préalpes médianes. The faults described here and their associated stresses are linked to the fold and thrust development in the Préalpes médianes. Thrust faults propagate with folds developing simultaneously. Strike-slip zones form lateral tear faults associated with lateral termination of fold related thrusts and are located for example in structural tranfer zones such as *en échelon* relays.

(iv) Comparison of results from fault analysis in the Préalpes médianes with data from earthquakes and fault orientations from the Molasse basin and the Jura fold-and-thrust belt north of the study area, reveals striking similarities both in fault and stress orientation. In most field examples data on faults and calculated stress orientations can be related with a specific structural feature (strike-slip fault and/or thrust). It remains unclear however if these structural features developed during one single tectonic event or whether two or more successive, coaxial events are superposed. Thus we couldn't find clear evidence, so far, for strike-slip faults extending into the underlying autochthonous and allochthonous structural units (Gurnigel nappe, Ultrahelvetic and Subalpine flysch as well as molasse). The data on faults and striations from the SW edge of the Swiss Préalpes médianes shown here give evidence neither for nor against, a large fault extending into the bedrock of the Rhône valley south of Montreux.

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