Sedimentology, petrographic variability, and very-low-grade metamorphism of the Champsaur sandstone (Paleogene, Hautes-Alpes, France) : evolution of volcaniclastic foreland turbidites in the external Western Alps

Alexander Waibel

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UNIVERSITÉ DE GENÈVE
DÉPARTEMENT DE MINÉRALOGIE

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et WALTHER WILDI

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THÈSE

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pour obtenir le grade de Docteur ès Sciences de la Terre

par

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La faculté des sciences, sur le préavis de Messieurs M. VUAGNAT, professeur ordinaire (Département de minéralogie) et W. WILDI, professeur ordinaire (Département de géologie et paléontologie) codirecteurs de thèse, R. CHESSEX, professeur ordinaire (Département de minéralogie), J. HUNZIKER, Professeur (Université de Lausanne), C. KERKHOVE, professeur (Université de Grenoble) et J. MARTINI, docteur ès sciences (Service géologique d'Afrique du Sud, Prétoria) autorise l'impression de la présente thèse, sans exprimer d'opinion sur les propositions qui y sont énoncées.

Genève, le 5 décembre 1989

Le Doyen:
Pierre BURI

Thèse N° 2392

TO MY PARENTS, WITH LOVE

FOREWORD

The work described in this Ph.D. dissertation was carried out at the Department of Mineralogy, University of Geneva, Geneva, Switzerland, where I was granted a teaching assistantship in October, 1985. In addition to the Grès du Champsaur, I sampled the Grès de St. Didier and the Grès d'Annot near the villages themselves. Similarities and differences are described briefly herein, where appropriate in the text. The conglomerates from St. Antonin and the Post de Clumanc were also sampled with the intention of dating the andesite and diabase pebbles by the potassium-argon method, in collaboration with Dr. D. Fontignie. These results will be published elsewhere. Furthermore, I had the opportunity to examine similar mottled graywackes in the central Coast Ranges (Briones Sandstone) near San Jose, California, during an extended visit to my parents in Fremont, California. Preliminary results of this study are mostly outlined in Chapter 6. J. Martini's and G. Sawatzki's thin-section collection of the Taveyanne Sandstone were also briefly examined for the purpose of comparison.

The topic and basic approach of this thesis were suggested by Prof. M. Vuagnat, who has been working with the Grès de Taveyanne and associated rocks, off and on, for over forty years. The writer is grateful to him for advice and guidance during the course of this study. I am most fortunate to have benefitted from such invaluable experience. Of equal importance were the contributions by Prof. W. Wildi, who, given the sedimentological scope of the topic, kindly agreed to coadvise this thesis. I thank him for valuable suggestions, especially those regarding the recording of sedimentological data in the early stages of my work. Thanks are due to Dr. J. Martini (Pretoria), Prof. J. C. Hunziker (Lausanne), Prof. C. Kerckove (Grenoble), and Prof. R. Chessex (Geneva) for having assumed the responsibility of becoming a member of the panel of jurors.

I extend sincere appreciation to my friend and colleague Dr. J. Bertrand for informal discussions and his continuous interest in my work. I wish to thank Dr. R. Wernli for having determined the microfossils, and Dr. C. Müller (Frankfurt) for the determination of the nannofossils. Thanks are extended to Dr. S. Huon (Neuchâtel), Dr. H. Sarp (Musée d'Histoire Naturelle, Genève), Prof. F. Lippmann (Tübingen), Dr. G. Sawatzki (Freiburg i. Br.), Prof. B. Kübler and M. Geyer (both Neuchâtel) for their valuable help in the preparation and/or interpretation of x-ray diffraction data. R. Wernli and S. Huon have gone to great length in discussing the implications with me. I am grateful to Prof. P. Homewood (Fribourg) for having introduced the Grès du Champsaur to me in the field. I

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(I) SUMMARY

The Champsaur Sandstone, the turbidite formation under study, comprises an uppermost Eocene or lowermost Oligocene volcaniclastic graywacke that was deposited in a migrating foreland basin at the front of an active fold- and thrust belt in the Subalpine Chains of the northern French Alps. It evolves from the slightly older and more internal Flysch des Aiguilles d'Arves into which it gradually passes towards the N. After a major erosional gap to the W, it passes into the slightly younger and more external St. Didier Sandstone which, in turn, eventually gives way to the Molasse Rouge. The Champsaur Sandstone is petrographically distinguished from these formations by its abundance in andesitic rock fragments which may locally comprise the greater part of the sedimentary rock. The andesitic volcanoes that furnished the sands and gravels formed part of a much larger volcanic arc that was erected adjacent and parallel to the western edge of the Adriatic plate in the Paleogene. Volcaniclastic intercalations of similar composition, age, and structural position are known from the Taveyanne Sandstone of the Swiss Alps, the St. Antonin Syncline of the Maritime Alps, the Petrignacola Sandstone of the northern Apennines, and the Tusa Facies of southern Italy and Sicily. In the Alps, the turbidite formations of predominantly andesitic composition progressively give way to younger and usually more external clastic formations in which the volcanic clasts are increasingly composed of ophiolitic material. These are the Val d'Illiez Sandstone of western Switzerland, the St. Didier Sandstone of the northern French Alps, and the Clumanc Sandstone of the Maritime Alps.

The Champsaur Sandstone is unconformably underlain by the Priabonian Schistes à Globigérines and Calcaires à Nummulites Formations, respectively, which are strongly transgressive onto the Pelvoux Massif in the north and its deformed Mesozoic sedimentary cover in the south. On the basis of structural position and gross lithological composition, three major sandstone units have been differentiated and sequentially numbered (1 to 3) according to age, becoming progressively younger from SE to NW. Sandstone units 1 and 2, including their Mesozoic and Priabonian substrata to which they are still attached, are entirely parautochthonous. With the arrival of the deformation front shortly after their deposition, they were detached, deformed, and transported in a westerly direction onto the third sandstone unit during postnummulitic thrusting in the late Oligocene-Miocene alpine compressional regime. In the course of further underthrusting and basinward migration of the fold- and thrust belt, the area under study was successively overrun in Oligocene-Miocene times by a series of Penninic, originally more internal nappes. This gave rise to several kilometers of overburden pressure which resulted in the development of secondary zeolite-facies assemblages in the volcaniclastic rocks.

Sedimentology

The Champsaur Sandstone constitutes a clearly stratified, regular alternation of turbiditic sandstones and shale, with frequent intercalations of pebbly sandstones, conglomerates and slumps. The sedimentary sequences display many of the properties that are characteristic of proximal, high-density turbidites: they have a high sand/shale ratio; the sandy layers are commonly coarse-grained, often conglomeratic and thick-bedded, and exhibit erosive features, like scouring, channeling, and amalgated beds; truncated basal Bouma sequences are generally the rule; furthermore, small-scale vertical and lateral facies changes can be rapid.

The flysch successions onlap the underlying Schistes à Globigérines and/or Calcaires à Nummulites Formations in units 1 and 3, and are inferred to have axially filled a structural depression that was in all likelihood elongate and originally aligned parallel to the fold- and thrust belt. It is reasonable to assume that, prior to the deposition of the first turbidite beds, regional tilting of the basin floor towards the orogen occurred by thrust loading. In that even the lowermost shale breaks - which lie only a few tens of meters above the erosional unconformity of the Priabonian transgressive sequence - lack wave reworking, subsidence to depths below the storm wave base must have been rapid, or, conversely, postponement of the turbidite fill long.

A comprehensive sedimentological study was carried out in the turbidite succession of unit 3 by measuring 12 stratigraphic sections. As determined from the trend and spacing of isopachs, the slope consists of an essentially planar, slightly undulating surface that strikes approximately

N45°E and is inclined towards the SE at an angle of 2-7° with respect to the horizontal. The turbidites were introduced longitudinally from the SW and were laterally confined by this slope. On average, as one approaches the basin floor in a given vertical succession, the spread of paleocurrent readings tends to get increasingly tighter in a direction aligned subparallel to the slope. The average paleocurrent direction of the unobstructed flows is towards the N23°E. It is felt that the vast majority of sediment gravity flows were introduced laterally into the basin from its internal margin, by an arrangement of several point or line sources along the deformation front of the fold- and thrust belt.

It is estimated that the total width across the Nummulitic Sea was at least 20 km from coast to coast, if not more; prior to the turbidite fill, its depth is assumed to have initially been at least 900 m at its deepest part. In relation to older and more internal lateral equivalents, it is thought that the Champsaur basin was comparatively narrow and shallow, whereby the depth at which the very last turbidite beds were deposited cannot have greatly exceeded that of the storm wave base.

Petrography and petrographic variability

The range of compositional variation is generally wide and extremely rapid between successive sandstone units in the direction of thrusting. While there is relatively little internal compositional variation within a given sandstone unit, compositional variations are abrupt when major thrust planes are crossed, which is due to the characteristic time lag between deposition and subsequent underthrusting of the sandstone units. In sandstone unit three, lithological variations during deposition of nearly 650m of sediment were recorded as a function of stratigraphic level and paleocurrent direction. It turns out that, whereas irregular lithological fluctuations take place between samples immediately overlying each other, overall lithological variations are essentially gradual between the base and top of this turbidite succession. Furthermore, there is no apparent dependence of petrographic variability on paleocurrent direction; all components are fully contained within the same directional spread encompassed by the turbidity currents. The evenly distributed pattern is an indication that the exposure of rock materials was essentially uniform in the hinterland and along the length of the coast at the source.

The clastic material contained in the Champsaur and St. Didier Sandstones may ultimately be traced back to four different parent sources: (1) andesitic volcanoes, (2) a Variscan basement massif, (3) ophiolites, and (4) sedimentary outcrops, whereby (1) and (2) are volumetrically the most significant.

Most of the volcanic components were derived from basaltic, calc-alkaline andesites; plagioclase, augite, and, to a lesser extent, hornblende comprise the characteristic phenocrysts. The fragments are entirely epiclastic. Contrary to the belief of numerous previous workers, no signs indicative of volcanic activity concurrent with the deposition of the turbidite beds were observed, such as submarine lava flows, intrusive bodies, pyroclastic fallout deposits, and the like. The fragments were eroded from solid andesitic masses generally lacking vesicular or scoriaceous structure, presumably mostly lava flows, with little, if any, evidence of explosive violence, such as volcanic ash, lapilli, or other ejecta. Andesitic detritus appears in sandstone unit 2 and rises to substantial proportions in unit 3. Andesitic fragments are totally lacking in the St. Didier Sandstone, indicating that, by the time the outward propagating depositional center reached the area of Devoluy, the andesitic source had been removed once and for all.

Fragments of granite, granodiorite, quartzite, leucogranite, granite-aplite, granitic gneiss, mica-schist, epidosite, rhyolite, dacite, globular porphyry, granophyre, and microgranite are all assigned to one and the same Variscan basement massif that furnished most of the remaining rock material in Devoluy and the Champsaur. Sandstone unit 1 is composed almost exclusively of these crystalline rocks. The quantities gradually decrease in units 2 and 3 before rising close to their initial values in the St. Didier Sandstone. The variation displayed by Variscan components essentially counters the progressive rise and fall in the amount of andesite. It is therefore thought that the massive addition of andesite is the immediate controlling factor for petrographic variability, by effectively suppressing the material derived from a crystalline basement source. Andesites appear in unit 2 and increase regularly until ultimately they are removed in equal amounts. It is conceivable that the extensive Variscan basement that had acted as the major

source from the start was partially covered by an andesitic volcano or overrun by an andesitic nappe, which was subsequently removed by erosion or underthrusting.

The ophiolitic detritus mostly comprises fragments derived from the destruction of submarine basalt, which is loosely referred to as "diabase". Arborescent, spherulitic, and intersertal textures reflect the diversity of concentric internal structures in the original pillow lavas from which these basaltic rocks were derived. There are also minor amounts of serpentinite, chloritite, and radiolarian chert; gabbro, ophicalcite, and prasinite are additionally known to occur in lateral equivalents where some of the ophiolitic components may retain a subduction-related, high-pressure metamorphic overprint. The characteristic spectrum of ophiolite members is the justification for linking their genesis to true ophiolite suites. The quantities of ophiolite fragments are minor, almost negligible in unit 1 and increase regularly from one unit to the other in the direction of thrusting.

A striking characteristic of the Champsaur and St. Didier Sandstones is their deficiency in sedimentary rock fragments which comprise an assortment of arenaceous and carbonate rocks. It is believed that most were derived from local Mesozoic and Priabonian units, either from the underlying autochthonous sediments or from parautochthonous thrusts; otherwise, it is conceivable that more internal Penninic or even Austroalpine units supplied additional amounts. Similar to the variation displayed by the quantities of ophiolitic material, sedimentary rock fragments were introduced to successive sandstone units in increasing amounts.

Provenance

In any given sandstone unit, the bulk of all rock materials can be assigned to either a basement massif or andesitic source. Any paleogeographic reconstruction must therefore make allowance for extensive outcrops of such rock types in the immediate vicinity of the Champsaur. Though there is little doubt that, during the intitial Priabonian transgression onto the Pelvoux massif, coarse terrigenous clastics were left in the wake of its retreating coastal cliffs, numerous lines of evidence suggest that shortly thereafter, i.e. during the deposition of the Champsaur Sandstone, sands and gravels were derived from internal terrains. It is thought that the crystalline components were for the most part shed from an external Variscan basement massif that was located to the SE of the Champsaur, on the internal side of the sedimentary basin, in a region that is now deeply buried by Penninic thrusts. It is argued that, during the deposition of the Champsaur Sandstone, both the Variscan and andesitic rock masses must have been close to sea level and the stable foreland, and thus in no tectonic position that would allow for Penninic subsurface structures thousands of meters thick. Therefore if, originally, the andesitic volcanoes were truly situated somewhere near the Penninic/Austroalpine boundary, they must have been thrust over the Penninic units before sliding down to their frontal position in the foreland. Emplacement of an andesitic nappe by long-distance overthrusting and/or gravitiy sliding is not required if, alternatively, eruption of the andesitic flows initially occurred closer to the depositional basin in the foreland, in a region neighboring the Ultrahelvetic Zone and lower Penninic nappes.

The ophiolite fragments were in all likelihood derived from accreted terrains, in particular the higher Penninic units, and it is speculated that a back-arc basin or an obducted ophiolite slab might have furnished small amounts. The sedimentary rock fragments, by contrast, were mostly shed from more local thrusts. With the passage of time, ophiolitic and sedimentary rock fragments were increasingly introduced to the Champsaur and St. Didier Sandstones in subordinate amounts. This is interpreted to reflect the progressive advance, uplift, and erosion of internal thrusts.

Metamorphism

The metamorphic assemblages are confined to strata of appropriate bulk composition. They are thus restricted to sandstone unit 3 and the westernmost portion of unit 2, where the percentage of inherently unstable andesitic debris is sufficiently high to have brought about reactions involving these constituents. Within these sandstone bodies, two local assemblages are irregularly disposed side-by-side: the "vert facies" and mottled zeolite facies. Due to the limited stratigraphic thickness and modest areal extent of volcaniclastic outcrops, no metamorphic zonations were detected in the Champsaur, neither vertically nor laterally.

The mottled zeolite-facies assemblage ideally comprises laumontite, pumpellyite, prehnite, albite, chlorite, and sphene, often with minute quantities of a micaceous mineral, possibly sericite; the primary ferromagnesian minerals are strongly altered but still largely preserved. The characteristic assemblage may deviate to a higher metamorphic grade in hydrothermal veins and adjacent reaction zones within the host rock, in which the assemblages are dominated by prehnite and pumpellyite, with minor epidote. The secondary mineral associations of the Champsaur Sandstone are therefore transitional between those that commonly characterize laumontite-and prehnite-pumpellyite-facies rocks. They are of higher rank than those that characterize the westernmost occurrences of the Taveyanne Sandstone, indicating a substantial departure from the pattern predicted on the basis of regional metamorphic zonations in the Swiss Alps and the French Alps of Savoie, where metamorphic grade increases progressively from west to east along the alpine arc. The temperature and effective load pressure to which the Champsaur Sandstone was subjected would correspond to a burial depth of at least 6000m, probably more.

The occurrences of the secondary minerals that are diagnostic of the mottled laumontite facies are as follows. Albite occurs everywhere as replacement of the original calcic plagioclase, except in strongly calcitized zones. Laumontite extensively replaces plagioclase and occurs as interstitial cement where it formed as an alteration product of a clay mineral, presumably montmorillonite. It is thought that laumontite initially invaded the fine-grained sedimentary matrix prior to its partial penetration into framework clasts as replacement of calcic plagioclase. The familiar deficiency of laumontite within larger andesite clasts results from their lack of potentially reactive clay minerals and their ability to inhibit the infiltration of reactive solutions. Chlorite occurs as an alteration product of volcanic glass, as cement, and as replacement of ferromagnesian minerals and plagioclase. Sphene formed as a by-product in the alteration of the sedimentary matrix and original volcanic glass to chlorite, but apparently less so or not at all during chloritization of plagioclase, hornblende, and augite. Within the ordinary graywacke, pumpellyite primarily occurs as an alteration product of laumontite, plagioclase, and chlorite. In reaction zones immediately adjacent to hydrothermal veins, pumpellyite may replace any detrital constituent except for quartz. In these reaction zones, aggregates of prehnite may suppress or replace masses of pumpellyite. However, apart from in veins and the adjacent reaction zones, prehnite is sparse and its occurrence is confined to replacement of plagioclase and laumontite within the country rock.

The "vert facies" comprises local departures from the characteristic zeolite-facies assemblage, in which the disappearance of calc-silicates coincides with the introduction of variable amounts of calcite, either because early, interstitial precipitation of calcite inhibits the transmission of reactive solutions, or because the associated rise in the activitiy of CO_2 significantly reduces the stability of zeolite-facies assemblages. Ideally, it is characterized by the following assemblage: calcite, chlorite, albite, sphene, and sericite; the primary ferromagnesian minerals have been largely replaced.

The "vert facies" is restricted to: (1) thin sandstone beds intercalated in major shale sequences; (2) the upper and lower calcitized margins of thick sandstone beds adjacent to shale breaks; (3) in diagenetic concretionary nodules cemented by calcite; (4) locally, in massive sandstone sequences overlying nummulitic limestones; and (5) locally, in the vicinity of major faults. The amount of calcite observed in a given specimen displays a variation that is compatible with the distance travelled by solutions from the parent CaO-rich rocks. The possibility that the development of the "vert facies" could be favored in rock bodies subjected to higher tectonic pressures may essentially be ruled out, even in the vicinity of faults, where it is rather thought that solutions were able to diffuse more freely, impregnating the adjacent rocks with calcite.

It is thought that, within a finite flysch succession of the Champsaur, all graywackes were originally characterized by similar bulk rock compositions. The irregular distribution of the "vert" and mottled zeolite facies assemblages is not governed by variations in the chemical characteristics of the original sediment. It is merely the disposition of associated carbonates, marls, and faults that determines the metamorphic course taken by the graywackes. One must assume that most observable chemical deviations between the two facies gradually arose during progressive metamorphism.

(II) FRENCH SOMMAIRE

Les grès du Champsaur constituent une formation turbiditique d'âge éocène terminal ou oligocène basal. Ces grauwackes volcano-détritiques se sont déposées dans un bassin d'avant-pays subalpin migrant, en avant du front orogénique alpin plissé et chevauché. Au nord, ils passent progressivement aux Flysch des Aiguilles d'Arves légèrement plus internes et plus vieux. A l'ouest, une zone d'érosion les sépare des grès de Saint-Didier plus externes, qui évoluent finalement vers la Molasse Rouge. Les grès du Champsaur se différencient pétrographiquement de ces différentes formations par une très forte proportion de débris andésitiques. Le matériel andésitique provient du démantèlement d'un arc volcanique d'âge paléogène, situé sur la bordure occidentale de la plaque adriatique. Des intercalations volcano-détritiques équivalentes, tant aux points de vue de la pétrographie, de la stratigraphie, que de la position structurale, sont connues dans l'édifice alpin. Il s'agit des grès de Taveyanne des alpes suisses et savoyardes, des grès du synclinal de Saint-Antonin des Alpes-Maritimes, des grès de Petrignacola de l'Apennin septentrional et les grès de Tusa de l'Italie du sud et de la Sicile. Dans l'arc alpin, les formations de turbidite à matériel andésitique passent progressivement à des formations détritiques généralement plus jeunes et plus externes, lesquelles s'enrichissent progressivement en matériel ophiolitique. Ce sont les grès du Val d'Illiez de Suisse occidentale, les grès de Saint-Didier des Alpes occidentales françaises ainsi que les grès de Clumanc des Alpes-Maritimes.

Les grès du Champsaur reposent en discordance angulaire sur les Schistes à Globigérines et les Calcaires à Nummulites qui sont fortement transgressifs sur le massif du Pelvoux au nord et sa couverture mésozoïque au sud. Trois unités principales peuvent être distinguées sur la base de leur position structurale et de leur composition lithologique; l'âge devient progressivement plus jeune en direction du nord-ouest. Les grès de l'unité 1 et 2, ainsi que leurs substrats nummulitiques et mésozoïques, sont entièrement parautochtones. Peu après leur sédimentation, ils ont été détachés, déformés et transportés vers l'ouest sur l'unité 3 qui est autochtone par rapport au massif du Pelvoux, durant la phase compressive alpine à l'Oligocène supérieur au Miocène. Ces unités furent ensuite recouvertes par les unités penniques, cette surcharge a induit le développement des faciès métamorphiques à zéolites caractéristique des roches volcano-détritiques.

Sédimentologie

Les grès du Champsaur constituent une alternance bien stratifiée de grès turbiditiques et de marnes, avec de fréquentes intercalations de grès grossiers conglomératiques, de conglomérats et de faciès de glissement synsédimentaires (slumps). La séquence sédimentaire présente de nombreux caractères typiques de turbidites proximales de haute densité avec un rapport grès sur marnes élevé. Les bancs gréseux sont généralement des sables grossiers, souvent conglomératiques et en bancs épais, avec de nombreuses figures érosives telles que "scours", chenalisations et bancs amalgamés. La séquence de Bouma tronquée est généralement la règle et les changements latéraux et verticaux de faciès peuvent être très rapides.

Dans les unités 1 et 3, les turbidites reposent en "onlap" sur les Schistes à Globigérines et/ou sur les Calcaires à Nummulites. Ils ont comblé axialement une dépression structurale qui était vraisemblablement allongée parallèlement au front orogénique plissé et chevauché. Il est raisonnable de penser que le basculement régional du substrat vers la zone interne s'est produit en réponse à une surcharge tectonique des nappes penniques. Les interstratifications marneuses à la base de la série ne présentent jamais de figures sédimentaires liées aux tempêtes, ce qui permet de conclure soit à une subsidence très rapide du fond, soit à un long délai avant le début du comblement turbiditique.

Une analyse sédimentologique complète a été menée dans l'unité 3 dans laquelle 12 sections furent levées en détail. Sur la base de la carte des isopaques, la pente sédimentaire apparaît comme une surface essentiellement plane, très légèrement ondulée, orientée N45°E avec une inclinaison d'environ 2° à 7° vers le sud-est. Les turbidites sédimentées en direction longitudinale depuis le sud-ouest étaient confinéees latéralement par cette pente. La moyenne des directions des paléocourants est orientée N23°E. Cette topographie fut rapidement comblée et les figures des paléocourants, très réguliers dans les cent premiers mètres, montrent une grande dispersion au sommet de la série. Il semble que la grande majorité des turbidites ont été introduites latéralement dans le bassin à partir de sa marge interne, par plusieurs sources situées le long du front de déformation.

On peut estimer que la largeur totale de cette partie de la mer nummulitique s'élevait d'une côte à l'autre à au moins 20 km, si ce n'est plus. Avant le comblement turbiditique, sa profondeur était initialement d'au moins 900 m à son point le plus bas. Comparé à des équivalents latéraux plus anciens et plus internes, le bassin du Champsaur était probablement plus étroit et moins profond. La profondeur à laquelle les dernières couches turbiditiques ont été déposées ne pouvait pas dépasser de beaucoup celle de la base de l'action des vagues de tempête.

Pétrographie et variabilité pétrographique

La variation de composition minéralogique entre différentes unités de grès est grande et extrêmement rapide d'une unité à l'autre en direction du sens de chevauchement. Tandis qu'à l'intérieur d'une unité de grès donnée cette composition varie relativement peu, la variation de composition pétrographique est très nette lorsque l'on atteint les plans de chevauchement majeurs; phénomène dû au décalage temporel entre le processus de sédimentation et les mouvements tectoniques postérieurs amenant les unités à se chevaucher. Dans la succession des turbidites de l'unité 3, les variations lithologiques, survenues lors de la sédimentation sur environ 600 m d'épaisseur, ont été déterminées en fonction du niveau stratigraphique et de la direction des paléocourants. Tandis que des fluctuations lithologiques irrégulières ont lieu entre les échantillons immédiatement superposés, les variations lithologiques sont généralement graduelles entre la base et le sommet de l'ensemble de la succession. D'autre part, il n'y a pas de dépendance apparente de la variation pétrographique par rapport à la direction du paléocourant; tous les composants sont représentés dans une direction donnée de courant turbiditique. Ce schéma de distribution régulière indique que la répartition des roches affleurant dans les bassins versants étaient essentiellement uniforme dans l'arrière-pays et le long de la côte.

Le matériel clastique contenu dans les grès du Champsaur et les grès de Saint-Didier a été alimenté par quatre sources différentes; on distingue, en effet, du matériel détritique provenant 1) de volcans andésitiques, 2) d'un massif de socle varisque, 3) d'ophiolites, et 4) de roches sédimentaires, les sources 1) et 2) étant volumétriquement les plus significatives.

La plupart des composants volcaniques proviennent d'andésites calco-alcalines basaltiques; les phénocristaux caractéristiques étant le plagioclase et l'augite, parfois la hornblende. Les fragments sont entièrement épiclastiques. Contrairement à certaines théories, aucune preuve attestant une activité magmatique (coulées de laves sous-marines, corps intrusifs, dépôts de projections pyroclastiques, etc.) concomitante à la sédimentation des turbidites n'a pu être mise en évidence. Les fragments clastiques, provenant de l'érosion de masses andésitiques déjà consolidées, ne présentant pas de vésicules ou de structure scoriacée, il devait probablement s'agir le plus souvent de laves; il n'y a guère d'évidence de l'existence de tephra (lapillis, cendres, etc.) dus à une activité explosive. Les débris andésitiques font leur apparition dans l'unité de grès 2 et leur proportion augmente de façon sensible dans l'unité 3. Les fragments andésitiques sont totalement absents dans les grès de Saint-Didier indiquant que lors du déplacement du centre de sédimentation, qui a atteint le Devoluy, la source andésitique avait déjà été complètement érodée ou recouverte par chevauchement.

Les fragments de granite, granodiorite, leucogranite, granite aplitique, gneiss granitique, micaschiste, épidosite, rhyolite, dacite, porphyre globulaire, ganophyre et microgranite sont sans doute tous originaires du seul et même massif varisque qui a fourni la majorité du matériel détritique dans le Devoluy et le Champsaur. L'unité de grès 1 est composée presqu'exclusivement de ces roches cristallines. Les quantités décroissent graduellement dans les unités 2 et 3, pour atteindre à nouveau des taux proches de leurs valeurs initiales dans les grès de Saint-Didier. La variation des teneurs des composants varisques contrebalance la hausse et la baisse progressives de la proportion d'andésites. Il est donc estimé que l'adjonction massive d'andésites est le facteur déterminant de la variabilité pétrographique, car elle supprime efficacement le matériel provenant du soubassement cristallin. Les andésites apparaissent dans l'unité 2 en augmentant

régulièrement, atteignent un maximum, et finissent par disparaître en suivant une courbe de sens opposé. Il est concevable que le vaste massif de socle varisque qui avait été la source principale dès le début était partiellement couvert par un volcan ou une nappe de charriage andésitique qui disparut ultérieurement, soit par érosion, soit enfouie sous un chevauchement.

Les débris ophiolitiques sont constitués principalement par des fragments dérivés de la destruction de roches sous-marine basaltiques que l'on dénomme de façon plutôt impropre "diabases". Les textures arborescentes, sphérolitiques et intersertales révèlent la diversité des structures internes concentriques dans les coussins caractéristiques de ces laves basaltiques. On peut également remarquer de petites quantités de serpentinites, de chloritites et de radiolarites; des gabbros, de l'ophicalcite et de la prasinite ont été par ailleurs observés dans des équivalents latéraux où certains composants ophiolitiques peuvent avoir une paragenèse de haute pression résultant d'une subduction antérieure. L'ensemble caractéristique de ces éléments permet de déduire qu'ils dérivent de vrais complexes ophiolitiques. Les quantités de fragments ophiolitiques dans l'unité 1 sont mineurs, voire négligables, et augmentent régulièrement d'une unité à l'autre en suivant le sens de chevauchement. Cependant même dans l'unité 3, la proportion de ces débris ne dépasse guère 1 %. Ce n'est que dans les grès de Saint-Didier qu'ils sont relativement abondants.

Une caractéristique frappante des grès du Champsaur et de Saint-Didier est leur pauvreté en fragments d'origine sédimentaire. Ces derniers comprennent diverses roches gréseuses et carbonatées dont on peut supposer que la plupart provenaient d'unités mésozoïques et priaboniennes locales, c'est-à-dire soit des sédiments autochtones situés endessous, soit des nappes parautochtones. Il est de plus concevable que d'autres fragments dérivaient d'unités penniques plus internes ou même d'unités austroalpines. Comme c'est le cas pour l'augmentation progressive du matériel ophiolitique, la proportion de fragments sédimentaires s'accroît de l'unité 1 à l'unité 3.

Origine

Chaque unité de grès est constituée de deux types de matériel rocheux présents en proportions dominantes; l'un provient d'un massif de socle, l'autre d'une source andésitique. Ainsi, pour toute reconstitution paléogéographique, il faut tenir compte de la présence de tels types de roches à proximité immédiate du Champsaur. Bien que durant la transgression initiale priabonienne sur le Pelvoux et ses abords il soit pratiquement certain que le retrait des falaises ait produit du matériel clastique terrigène grossier, de nombreuses données suggèrent que peu après, c'est-à-dire durant le dépôt des grès du Champsaur, les sables et graviers provenaient de terrains plus internes. La plus grande partie des composants cristallins est issue, semble-t-il, d'un socle varisque externe, situé au SE du Champsaur, à la marge interne du bassin sédimentaire, d'une région maintenant profondément enfouie sous les nappes penniques. On montre que, pendant le dépôt des grès du Champsaur, tant le massif varisque que le complexe andésitique devaient être proches du niveau de la mer et de l'avant-pays stable; ils ne pouvaient donc être dans une position tectonique permettant la présence en profondeur d'unités penniques de subsurface épaisses de plusieurs milliers de mètres. C'est pourquoi, si les volcans andésitiques étaient véritablement à l'origine situés à proximité de la limite entre le Pennique et l'Austroalpin, ils ont nécèssairement dû être charriés par dessus des unités penniques, avant de se mettre en position frontale dans l'avant-pays. Par contre, il n'est pas nécessaire d'envisager la mise en place d'une nappe andésitique par charriage et/ou glissement gravitaire sur une longue distance si le volcanisme andésitique a eu lieu initialement plus près du bassin de dépôt dans l'avant-pays, dans une région voisine de la zone ultrahelvétique et des nappes penniques inférieures.

Les fragments ophiolitiques dérivent probablement de terrains empilés et exhaussés, et plus particulièrement des unités supérieures; on peut aussi supposer qu'un bassin d'arrière-arc ou qu'un lambeau obducté d'ophiolite auraient fourni de petites quantités de matériel. Les fragments de roches sédimentaires, en revanche, sont issues de nappes plus proches. Au cours du temps, le matériel ophiolitique et sédimentaire a alimenté les grès du Champsaur et de Saint-Didier en proportion croissante mais toujours subordonnée. Cette augmentation résulte de l'avancée progressive, de l'élévation, et de l'érosion des nappes internes.

Métamorphisme

Les paragenèses métamorphiques se limitent aux strates d'une composition chimique globale appropriée. Elles sont de ce fait limitées à la troisième unité de grès et à la partie la plus occidentale de l'unité 2, où le pourcentage de débris andésitiques instables est suffisamment élevé pour avoir provoqué des réactions à partir de ces constituants. Dans ces unités de grès, on trouve deux paragenèses locales irrégulièrement distribuées: le "faciès vert" et le faciès moucheté à zéolites. Etant donné la faible épaisseur stratigraphique et la surface limitée des affleurements volcano-détritiques, on n'observe pas dans le Champsaur de zonation métamorphique, ni verticale, ni latérale.

La paragenèse du faciès moucheté à zéolites, dans le cas idéal, comprend les minéraux suivants: laumontite, pumpellyite, prehnite, albite, chlorite et sphène, souvent avec d'infimes quantités d'un minéral micacé, peut-être de la séricite; les minéraux ferromagnésiens primaires sont fortement altérés mais néanmoins encore largement préservés. La paragenèse peut tendre vers un facies plus élevé dans les fissures hydrothermales et dans les zones de réaction adjacentes à l'intérieur de la roche encaissante où pumpellyite et prehnite sont dominantes, avec un peu d'épidote. Les associations minérales secondaires des grès du Champsaur sont donc transitionelles entre celles qui caractérisent normalement les roches à faciès laumontite et les roches à faciès pumpellyite-prehnite. Elles sont d'un degré plus élevé que celles qui caractérisent les affleurements les plus occidentaux des grès de Taveyannaz, ce qui indique une déviation notable par rapport au schéma prévu en se fondant sur les zonations métamorphiques régionales des Alpes suisses et des Alpes françaises de la Haute-Savoie, où le degré de métamorphisme augmente progressivement d'ouest en est le long de l'arc alpin. La température et la pression effectives auxquelles les grès du Champsaur ont été soumis correspondraient à une surcharge d'au moins 6000 m.

Les minéraux secondaires caractéristiques du facies moucheté à laumontite se répartissent comme suit. L'albite remplace le plagioclase calcique originel, sauf dans les zones fortement calcitisées. La laumontite remplace le plagioclase et constitue un ciment interstitiel où elle s'est formée comme produit d'altération d'un minéral argileux, probablement de la montmorillonite. On peut penser que la laumontite a initialement envahi la matrice sédimentaire avant sa pénétration partielle dans les grains constitutifs en remplaçant le plagioclase calcique. La pauvreté caractéristique en laumontite des grains andésitiques résulte de leur manque de minéraux argileux potentiellement réactifs et de leur capacité d'inhiber l'infiltration de solutions réactives. La chlorite apparaît comme produit d'altération du verre de la pâte des éléments volcaniques, comme ciment, et en remplacement des minéraux ferromagnésiens et du plagioclase. Le sphène s'est formé lors de l'altération de la matrice sédimentaire et du verre volcanique mais moins ou pas du tout lors de la chloritisation du plagioclase, de la hornblende et de l'augite. A l'intérieur de la grauwacke ordinaire, la pumpellyite figure essentiellement comme produit d'altération de la laumontite, du plagioclase et de la chlorite. Dans les zones de réaction immédiatement adjacentes aux fissures hydrothermales, la pumpellyite peut remplacer n'importe quel constituant détritique mis à part le quartz. Dans ces zones de réaction, des agrégats de prehnite peuvent supprimer ou remplacer des masses de pumpellyite. Toutefois la prehnite est éparpillée, sauf dans les fissures et les zones de réaction secondaires, et elle ne se trouve qu'en remplacement du plagioclase et de la laumontite à l'intérieur de la roche encaissante.

Le "faciès vert" comporte une variation locale de la paragenèse à zéolites caractéristique, où la disparition des silicates de chaux coïncide avec le développement de quantités variables de calcite, disparition due soit à la précipitation interstitielle de calcite qui inhibe la circulation des solutions réactives, soit à l'augmentation de l'activité du CO_2 qui réduit considérablement la stabilité des paragenèses appartenant au faciès à zéolites. Dans le cas idéal, le "facies vert" est caractérisé par l'association suivante: calcite, chlorite, albite, sphène, et séricite; les minéraux ferromagnésiens ont été largement remplacés.

Le "faciès vert" est limité: (1) à de fine couches de grès intercalées dans d'épaisses séquences de schistes argileux; (2) aux marges supérieures et inférieures de puissantes couches de grès adjacentes aux interstratifications argileuses; (3) aux concrétions diagénétiques cimentées par la calcite; (4) localement, à des séquences de grès massives qui reposent sur des calcaires nummulitiques; et (5), localement, aux alentours des failles majeures. La quantité de calcite observée dans un échantillon donné montre une variation correlée avec la distance parcourue par les solutions à partir des roches parentées riches en CaO. L'hypothèse que le développement du "facies vert" soit favorisé par des surpressions tectoniques peut être écartée, même près des failles, où il semble plutôt que les solutions pouvaient diffuser plus librement et imprégner les roches adjacentes en y déposant de la calcite.

Tout indique que dans une série donnée de turbidites du Champsaur, toutes les grauwackes étaient à l'origine caractérisées par des compositions globales similaires. La répartition irrégulière du "faciès vert" et du faciès moucheté à zéolites n'est donc pas déterminée par les variations chimiques du sédiment originel. C'est simplement la disposition des lits de marnes, des failles et des roches carbonatées qui détermine l'évolution métamorphique suivie par les grauwackes. Il faut admettre que la plupart des variations chimiques observées entre les deux faciès se sont produites graduellement lors du métamorphisme.

1. INTRODUCTION

1.1. General Geological Context

The Champsaur Sandstone, or Grès du Champsaur, the turbidite formation under study, is situated in the external French Alps, about 90 km to the SE of Grenoble and 25 km to the NE of Gap, in the Département des Hautes Alpes (fig. 1). It is named after the Champsaur Valley formed by the Upper Drac. The turbidite succession terminates the Tertiary sedimentary cover of the external crystalline massif of Pelvoux. To the N, it passes more or less directly into the slightly older Flysch des Aiquilles d'Arves (see Barbier, 1956; and Derharveng et al., 1987)), and to the W, via a major erosional break, into the slightly younger Grès de St. Didier, i.e., St. Didier Sandstone (Vuagnat, 1947a; Fabre et al., 1985a). It is separated from the overlying internal Embrunais-Ubaye nappes by an olistostrome (Kerckhove, 1964, 1975; see also Kindler, 1988).

The Champsaur Sandstone is a volcaniclastic, turbiditic graywacke containing up to 62% andesitic rock fragments, with minor amounts of ophiolitic debris in the order of 1%. It forms part of a much larger, discontinuous, curvilinear flysch belt known for its volcaniclastic intercalations along much of the alpine arc (Stalder, 1979; Giraud, 1983; Vuagnat, 1985). In the Swiss and northernmost French Alps, it closely resembles the well studied Taveyanne Sandstone and associated rocks (de Quervain, 1928; Vuagnat, 1952; Martini 1968, 1972; Martini & Vuagnat 1964, 1965, 1967, 1970; Sawatzki, 1975; Sawatzki and Vuagnat, 1971; Siegenthaler, 1972; Lateltin, 1988). Farther south, in the St. Antonin Syncline of the Maritime Alps, abundant andesitic debris is known to occur in clastic intercalations of approximately the same age (Goguel, 1952; Vernet, 1964; Duplaix & Gennesaux, 1966; Alsac et al., 1969; Boucarut & Bodelle, 1969). Compositionally similar volcaniclastic intercalations of approximately the same age are found in the Petrignacola Sandstone of the northern Apennines (Elter et al., 1964, 1969), which reappear in the Tusa Facies of southern Italy and Sicily (Ogniben, 1964).

In the Alps, there is a well documented, progressive change in sandstone composition with decreasing age (fig. 2). The turbidite formations of predominantly andesitic composition commonly give way to younger and more external clastic formations in which the volcanic clasts are composed increasingly of ophiolitic material. The clastic formations containing less or no andesite detritus are the Val d'Illiez Sandstone of western Switzerland and the Haute Savoie of France (Vuagnat, 1943; Martini, 1968; Sawatzki, 1975), the St. Didier Sandstone of the northern French Alps (Vuagnat, 1947a), and the Clumanc Sandstone of the southern French

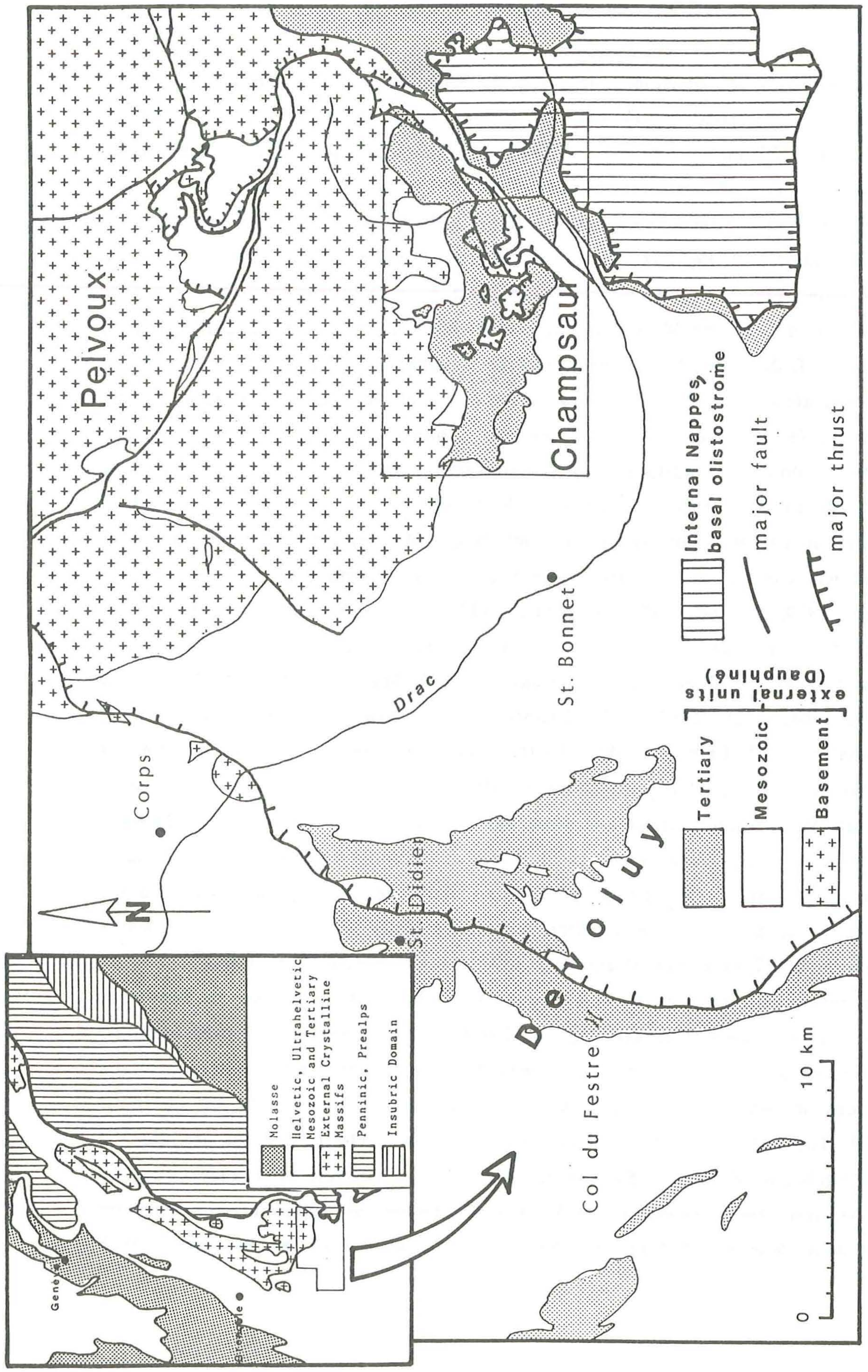


Fig. 1. Simplified geological map showing distribution of Tertiary outcrops to the S and SW of the Pelvoux Massif, in the Subalpine Chains of Southeast France (after geological maps, 1: 50,000, St. Bonnet and Orcière quadrangles, respectively nos. 845 and 846). The rectangle in eastern portion of map delineates location of area depicted in figure 3.

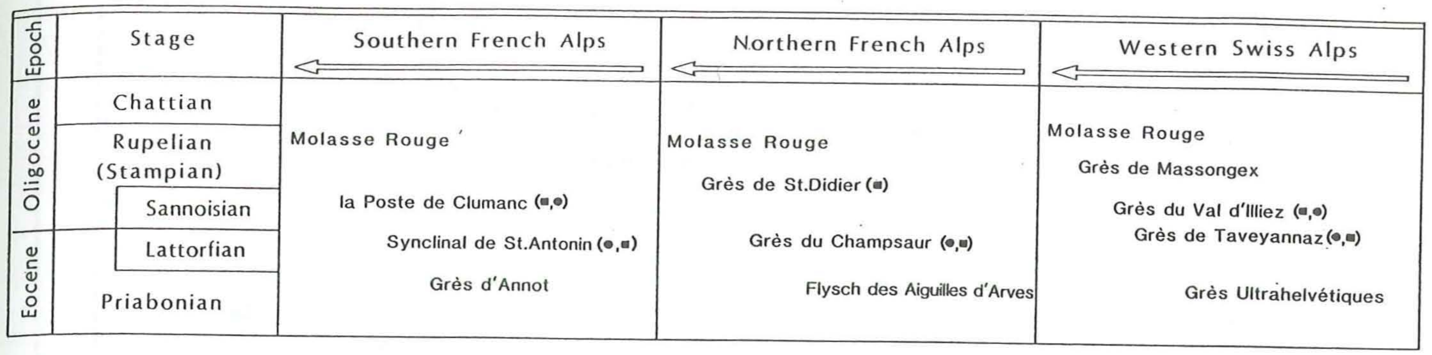
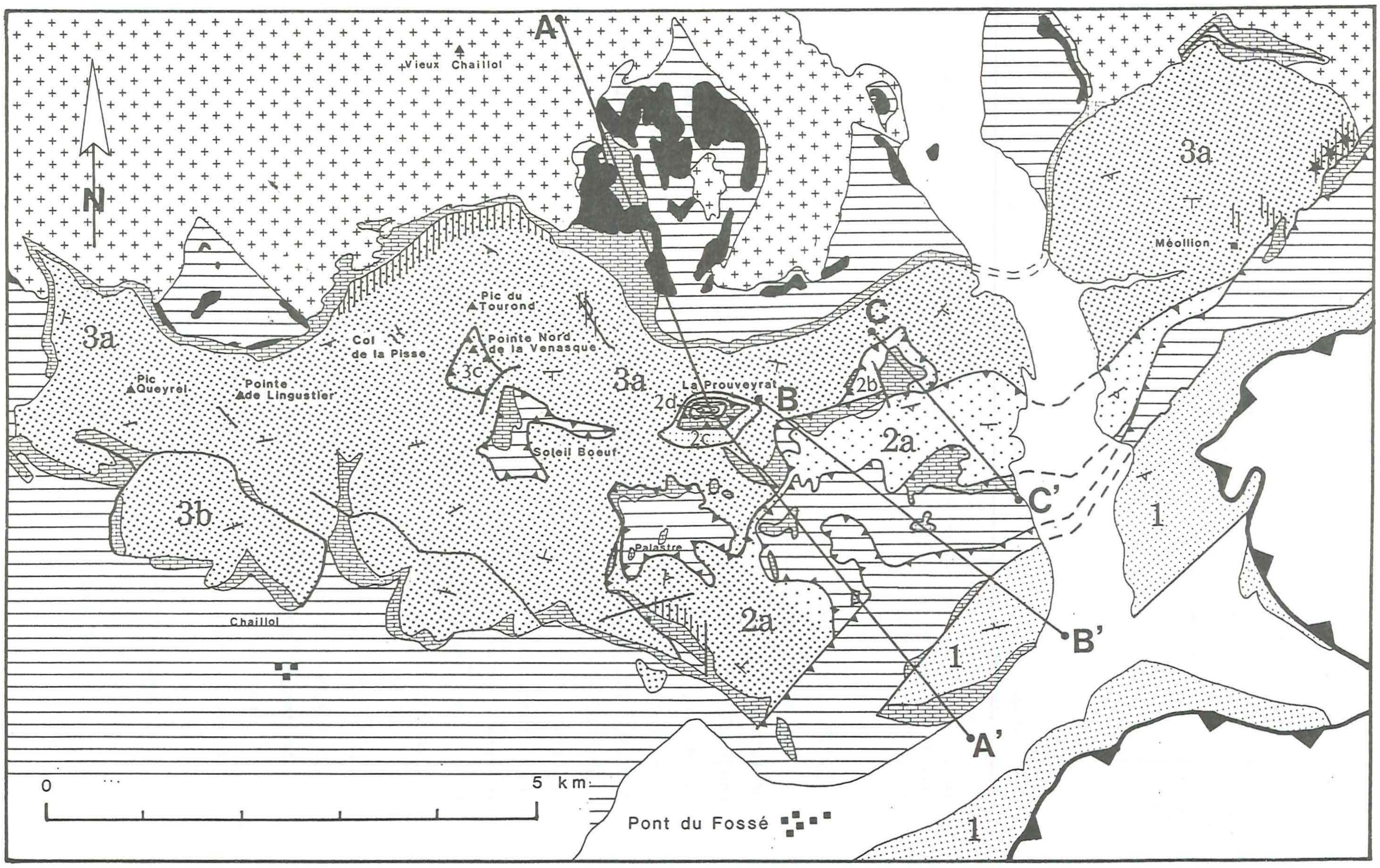


Fig. 2. Schematic portrayal of alpine foreland stratigraphy displaying progressive changes in relative positions of Tertiary basins and diagnostic compositional variations with age. Arrows indicate polarity of foreland basin shifts toward the more external zones of the Alps. Deposits containing andesitic debris are designated with a filled circle, those containing ophiolitic material with a filled square (based largely on Vuagnat, 1952; Pairis et al., 1984; Evans and Elliot, 1985; Chauveau, 1960; and Lateltin and Müller, 1987).

Alps (Chaveau & Lemoine, 1960; Bodelle, 1971;de Graciansky et al., 1971).

The entire spectrum of formations was deposited in one and the same network of migrating "peripheral" (Dickinson, 1974) foreland basins, in a fault- and fold-controlled foredeep adjacent and parallel to the orogenic belt. It has been shown that, in a given section of the Alps, the depositional environment shifts outward and becomes progressively younger and shallower towards the more external zones of the Alps (Vuagnat, 1952; Elliot and Graham, 1985; Apps and Ghibaudo, 1985). The outward transition is from open-marine, deep-water turbidite basins, through shallow-water sandstones deposited in near-shore environments, to alluvial red-beds of the Molasse Rouge (Elliot et al., 1985). In any given vertical section, the ideal Tertiary sequence (e.g. Pairis et al., 1984; Evans and Elliot, 1985; Apps and Guibaudo, 1985; Pairis, 1987) comprises, stratigraphically from bottom to top:

1) in local pockets, a fluviolacustrine continental facies (Poudingue d'Argens; conglomérats rouges);
2) strongly transgressive, shallow-water nummulitic limestones (Calcaires à Nummulites);
3) marine marls and schists deposited in deeper and quieter water farther offshore (Schistes à Globigérines, Marnes Bleues, Marnes à Foraminifères);
4) a clastic sequence of diverse origin as described directly above (mostly turbidites, such as the Champsaur, Taveyanne, Annot, and Val d'Illiez Sandstones); and



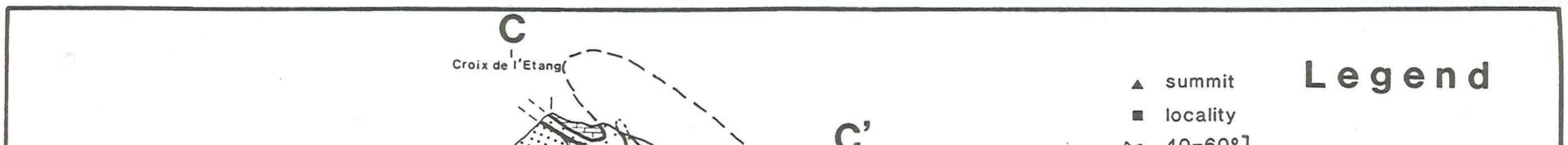


Fig. 3. Simplified geological map and structure sections showing the distribution of the Champsaur Sandstone and its relationships to associated rocks (based largely on Beuf, 1959, and B.R.G.M., 1: 50.000, Orcières quadrangle, XXXIV - 37, no. 846). The three major sandstone units have been sequentially numbered (1 to 3) according to age, becoming progressively younger from SE to NW; these, in turn, have been subdivided into subunits (a, b, or c), which are inferred to have suffered little displacement relative to the major unit (a). The percentages of andesitic debris refer to the percentages of rock fragments in the very coarse sand fraction, without the associated mineral debris.

5) at the base of the overlying internal nappes, the Tertiary sequence is often capped by a tectonically overprinted, chaotic sedimentary deposit, the "Schistes à Blocs" Formation, with a predominantly pelitic host matrix embracing blocs derived from mostly sedimentary sources (Kerckove, 1964, 1975; Kindler, 1988).

This sedimentary sequence has been attributed to rapid subsidence of the European continental margin (Vuagnat, 1952) due to isostatic downbending (see Beaumont, 1981) in response to regional loading at the front of an active thrust belt (e.g. Apps and Ghibaudo, 1985; Pairis, 1987), with additional deepening possibly resulting from an eustatic rise in sea level during the late Eocene (Homewood et al., 1985; Evans, 1987). The outward propagating structural depressions were mostly filled axially by prograding turbidites which onlap the underlying Schistes à Globigérines and Calcaires à Nummulites Formations (Stanley, 1961; Jean, 1985; Lateltin and Müller, 1987; Lateltin, 1988) by up to 30° (Apps and Ghibaudo, 1985).

1.2. Objectives

The Champsaur Sandstone is of interest for several reasons. Firstly, the andesite fragments contained in it and its lateral equivalents are virtually the only signs of a calc-alkaline volcanism predating the collision of the continental plates, with minor exceptions, such as the andesitic tuffs and flows of the Sesia Zone, and the andesite veins associated with the Val Bregaglia pluton (Vuagnat, 1985). In plate-tectonic terms, the general scarcity and unduly late appearance of andesites in the Eocene has always been somewhat of a problem in the Alps, where a subduction zone is widely known to have existed since the Early Cretaceous. Secondly, as is generally known, the unstable minerals in mafic rock fragments are sensitive to changes in temperature and pressure. The Champsaur Sandstone can thus serve to give reliable information on genetic conditions during regional metamorphism. Thirdly, since the Champsaur Sandstone is relatively undeformed and exposure is excellent, it lends itself nicely to studies concerning the ancient sedimentary environments and the processes which operated within them. It was in slightly older lateral equivalents, the Annot Sandstone (at Peïra-Cava), where Arnold Bouma (1962) was able to determine the classical sequence of sedimentary structures in turbidite beds.

Fig. 4. Outcrop directly adjacent to cabin on ridge between the Vieux Chaillol and Pic du Tourond (X=905.8; Y=276.4) displaying nummulitic transgression onto crystalline rocks of the Pelvoux Massif (see also Boussac, 1912, plate III, figure 2).

This Ph.D. dissertation has been subdivided into five major parts. The first part (Chapter 2) is devoted to the sedimentology of the Champsaur Sandstone. It is intended to complement similar sedimentological studies that were undertaken in the Champsaur Sandstone (Perriaux and Uselle, 1968; Butin-Kiener and Catalayud, 1983) and similar sediments elsewhere along the alpine arc (Radomski, 1961; Stanley, 1961; Bouma, 1962; Stanley and Bouma, 1964; Jean, 1985; Apps and Ghibaudo, 1985; Lateltin and Müller, 1987; Siegenthaler, 1972; Lateltin, 1988). Emphasis is on the sediment dispersal pattern and the topography of the basin floor. The second part (Chapter 3) comprises a petrographic study of the sandstone units. A detailed description of the myriad of individual clasts that make up the sedimentary rock has been kept at a minimum, since they are sufficiently similar to those in the Taveyanne Sandstone, which are described in great length by Vuagnat (1952) and Sawatzki (1975). Rather, in the third part of this dissertation (Chapter 4), importance has been attached to petrographic variability between and within individual units, because this has been shown to be of lithostratigraphic value by Vuagnat (1952) and Sawatzki (1975). In the fourth part (Chapter 5), the results of the sedimentological and petrographic studies are used to rediscuss the provenance of rock materials contained in these rocks. The last part of this thesis (Chapter 6) deals exclusively with the secondary mineral associations and chemical compositions of the metamorphosed rocks.

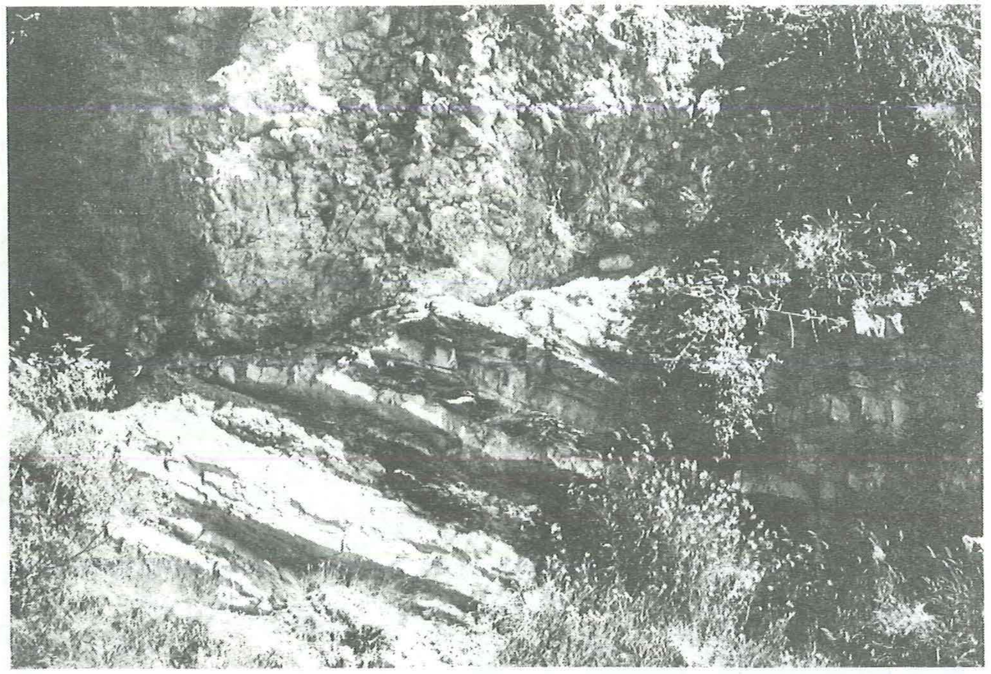


Fig. 5. Erosional angular unconformity (Combes Roranches) between local fluvial conglomerate (above) and slightly inclined Oxfordian (Argovian) strata (below). The overlying conglomerate of the Calcaires à Nummulites Formation (immediately to the left of photograph) is distinguished by its strongly calcareous matrix (as in fig. 4). One may therefore assume that this conglomerate, by contrast, is truly marine, and that the components were deposited farther offshore and partly "inherited" from the same stream.

1.3. Structural Setting of the Champsaur Sandstone

The Champsaur Sandstone is unconformably underlain by the Priabonian Schistes à Globigérines and Calcaires à Nummulites Formations, respectively. These, in turn, may locally overly coarse fluvial clastics, the "conglomerats rouges", the restricted occurrences of which presumably mark the localized inflow of streamlets into the Nummulitic Sea. Structurally, these formations represent an Eocene transgressive sequence onto the external crystalline massif of Pelvoux in the north (fig. 4) and its deformed Mesozoic sedimentary cover in the south (fig. 5). Where developed, both the "conglomerats rouges" and the transgressive basal conglomerate of the Calcaires à Nummulites Formation compositionally reflect the underlying rock material. Accordingly, locally derived crystalline clasts are for the most part confined to the north, with only minor concentrations in the south or in parautochthonous units that originally lay farther to the east or south.

The area under study is perhaps the first region where the "transgression nummulitique" was shown to overly an angular unconformity (Boussac, 1912) (fig. 5). The underlying "ante-nummulitiques" (pre-nummulitic) folds and thrusts are thought to correspond to the Pyrénéan-Provençal orogenic phase (Lemoine, 1972; Graham, 1978; Siddans, 1979; Gidon, 1979b). Following the main phase of deformation in the Paleocene, erosion prevailed, mostly obliterating the topography by the time the nummulitic transgression arrived (Barbier, 1956). During deposition of the lower nummulitic transgressive sequence, submarine synsedimentary blockfaulting resumed (Gidon and Pairis, 1976; Fabre et al., 1985a, 1985b; Kerckhove et al., 1978; Lateltin and Müller, 1987; Guardia and Ivaldi, 1987; Lami et al., 1987). At the appearance of the first turbidite units, some of these topographic irregularities were in all likelihood finally subdued. There was, however, regional tilting of the basin floor by a few degrees towards the orogenic belt by thrust loading prior to the deposition of the first turbidite beds.

With the arrival of the thrust belt, the sandstone units and their substrata were subsequently incorporated into thrust sheets and progressively overridden, presumably shortly after their deposition. This involved tectonic transport of at least 4 major parautochthonous units onto the Pelvoux Massif and its sedimentary cover, with additional units preserved in the klippes of the Soleil Boeuf (Gidon and Pairis, 1980), the Palastre, the Prouveyrat, and the Pointe Nord de la Venasque, plus an array of minor fragments that were caught up in major thrust planes (Beuf, 1959) (fig.3). The parautochthonous units structurally comprise the Tertiary transgressive sequence, its transgressed Mesozoic substrata to which it is still partly attached, and fragmentary portions thereof. These were detached, deformed, and transported in a westerly direction away from the orogenic belt (Gidon and Pairis, 1976, 1980; Gidon, 1979a, 1979b) during "post-nummulitic" thrusting in the late Oligocene-Miocene alpine compressional regime (see Graham, 1978; Siddans, 1979; Beach, 1981). Within each sandstone unit, however, alpine deformation is moderate, particularly the autochthonous unit which is virtually undeformed, except for a kink fold at Pic Queyrel and numerous tight, upright folds in the valley of Méollion. Outcrops are generally excellent or good.

In the course of further underthrusting and basinward migration of the fold- and thrust belt, the area under study was successively overrun by a series of Penninic nappes derived from more internal zones of the Alps. The first and lowermost Embrunais-Ubaye Nappes were emplaced in Oligocene-Miocene times and are still preserved in vast areas of the western Alps (Kerckhove, 1969, 1975). The original thickness of this tectonic pile must have been considerably greater, though, giving rise to several kilometers of overburden pressure. In the volcaniclastic rocks, the associated rise in temperature and pressure resulted in the recrystallization of the unstable constituents to zeolite-facies assemblages with extensive laumontitization. The Champsaur Sandstones have often been called "Grès Mouchetés" ("Mottled Sandstones") on account of the distinctive mottled appearance laumontite produces in the volcaniclastic rocks.

1.4. Geological Maps

The Champsaur Sandstone and underlying sediments (both Mesozoic and Tertiary) have been mapped in detail by Beuf (1959) and Butin-Kiener and Catalayud (1983). The geological map by Beuf (1959) is accompanied by petrographic descriptions and a host of stratigraphic columns and structure sections. His work has been accommodated, with minor modifications, in the geological map published by the B.R.G.M. in 1980: 1:50 000, Orcières quadrangle, XXXIV - 37 (No. 846). The Champsaur Sandstone also appears on the map published in 1905: 1:80 000, Gap quadrangle, No. 200. They are also shown on a simplified geological map (intended for nongeologists) at a scale of 1:100 000, which is included in the work by Debelmas et al. (1982).

The St. Didier Sandstone is shown in the St. Bonnet quadrangle, XXXIII -37 (No. 845), published by the B.R.G.M. in 1980 at a scale of 1:50 000.

For the geologist concerned with any aspect of the sedimentary rock, the best approach to initially become familiar with the outcrops is from the ski resort of Chaillol. From here he or she may take the woodland path towards the Col de la Pisse. Between the timber line and the latter, the rocks are extensively visible, both vertically and laterally.

2. SEDIMENTOLOGY OF THE CHAMPSAUR SANDSTONE

The Champsaur Sandstone constitutes a clearly stratified, regular alternation of turbiditic sandstones and shale, with frequent intercalations of pebbly sandstones, conglomerates, and slumps. The variation in thickness ranges from approximately 100 m or less in the parautochthonous units to over 650 m in the sandstone unit that is autochthonous with respect to the Pelvoux Massif

The sediments display many of the properties that are characteristic of proximal turbidites: they have a high sand/shale ratio; the sandy layers are commonly coarse-grained, often conglomeratic and thick-bedded, and may exhibit erosive features, like scouring, channeling, and amalgated beds; in the coarse-grained deposits, truncated basal Bouma (1962) sequences are generally the rule; furthermore, vertical and lateral facies changes can be rapid.

2.1. Lithological Units

2.1. Sandy and Gravelly Turbidites

The thickness of individual turbidite beds varies from a few centimeters to about 6 m. Amalgated sequences may be up to a few tens of meters thick.

Most commonly, the turbidite bed consists of a simple, graded Bouma Ta division of coarse sandstone or gravel overlying a sharp, flat, sometimes scoured or amalgated base with frequent sole marks. Often, the basal graded portion gradually passes upwards into finer-grained, parallel laminated or wavy sediment (division Tb). The latter part may, in turn, progressively give way to contorted, wavy, or "overturned" lamination or cross-stratification (division Tc). Biogenic structures are often found at the sandstone/shale interface. With increasing grain size and thickness of the turbidite deposits, the underlying sediment can easily be scoured down to 3 m by a single event. Though, for the most part, erosive power seems to increase proportionally with thickness and coarsest size grade of the turbidite bed, both coarse gravel and sand can form the channel-fill of the most deeply erosive beds.

The thick-bedded, coarse-grained beds show many of the sedimentary structures related to rapid deposition from concentrated, high-density turbulent or liquified flows, which are described in detail by D. R. Lowe, 1982 (see also Jean, 1985). The basal portions of the beds frequently contain continuous or patchy, indistinct concentrations of gravel and coarse sand which are due to surges and fluctuations during the initial stages of the high-density flow. The lower, gravelly horizons deposited largely by traction are gradually overlain by poorly sorted, massive sandstones deposited increasingly from suspension. In this horizon, fluid escape structures, such as dishes and pillars, are common.

2.1.2. Slumps

A multitude of slumps and debris flows were encountered throughout the sedimentary sequences, especially in the autochthonous unit. They vary in thickness from a few tens of centimeters to a few meters, i.e. within about the same range as the turbidite beds. The disturbances are restricted to a single bed or a well defined, planar, disrupted zone between two undisturbed beds. Pervasive, chaotic disruption characterizes the thicker units, with disordered, irregular accumulations of shale, sandstone, and gravel. In other cases, crude slump folds indicate that the sediment mass retained some internal coherence during movement down a gentle slope.

The disturbances are presumably due to liquification by the rapid expulsion of pore water soon after deposition, rather than to instability caused by minor diastrophic episodes; that is, most slumps probably result from collapse of a single turbidite bed.

2.1.3. Shale Horizons

Most turbidite successions contain a substantial amount of shale interstratified with the sandstone beds. Shaley sequences can attain a thickness of at least 70 m together with insignificant amounts of sandy material in the form of minor intercalated beds. They result from the intermittent deposition of low-density turbidity currents of low velocities transporting clay- and silt-sized particles in low concentrations, accompanied by slow, hemipelagic settling through the water column. The silty turbidites are often characterized by base-cut-out Bouma sequences; the sedimentary structures indicate rapid deposition of fine-grained sediment from traction and suspension, such as current-ripple cross-stratification, plane-parallel laminae, wavy or convolute laminae, and ripple-drift cross-lamination. Shallow-water sedimentary structures are lacking in the shale partings. Most, if not all of the silty and muddy turbidites are the distal or overbank equivalents of the associated sandy and pebbly gravity flows into which they gradually pass in a direction perpendicular and parallel to the general direction of flow (section 2.3.2).

A cursory examination with the polarizing microscope revealed detrital quartz, feldspar, carbonate, mica, glauconite, and epidote, in addition to other clasts which, on account of the small particle size, were not identifiable by conventional microscopic methods. The clay minerals that have been identified in shale partings by x-ray analysis are illite, chlorite, and one or more interstratified clay minerals consisting of layers of illite, montmorillonite, and chlorite (Aprahamian, 1974).

2.1.4. Rip-Up Clasts

Numerous rip-up clasts of diverse sizes, shapes, and consistencies were found in the massive sandstone beds, which are due to reworking of previous semi-indurated mud and silt deposits directly underneath. Small clasts and coherent, stratified bodies up to 4 m in diameter were detached, incorporated, and carried to a new depositional site by turbidity currents. Both the appearance and size of the reworked components are often closely related to the material and thickness of the shale horizon underlying the final site of deposition. This clearly excludes a source outside the area in which these clasts were deposited, i.e. they were not derived from erosion of older, preexisting rocks.

2.1.5. Sand Dikes and Sills

Rarely, sand dikes and sills intrude the overlying shaly sediment. Due to the relatively quick increase in burial pressure by rapid deposition of the overlying sediments, water-saturated, sandy sediment underlying semi-consolidated deposits of low permeability was suddenly injected upwards by the increased pore pressures (see Blatt et al., 1980, p. 186).

2.1.6. Olistoliths

Approximately 200 m above the Schistes à Globigérines Formation, in the stream bed at the "Aiguilles" (SW of Soleil Beouf), one pebbly limestone bloc was found intercalated in the flysch sequence (see also Lami et al., 1987). Its tabular dimensions measure approximately 5 m by 1 m. The micritic matrix is riddled with Tertiary foraminifera, the assemblage of which was kindly determined by R. Wernli in thin section (sample 146):

Globigerina sp.,
Chiloguembelina sp.,
Turborotalia sp.,
Miliolidés quinqueloculins,

in addition to a host of indeterminable benthonic foraminifera. Though, in all probability, the limestone predates the Upper Oligocene, it cannot be resolved whether it is Eocene or Oligocene in age.

It cannot be ruled out that the olistolith constitutes a reworked member of the Calcaires à Nummulites Formation. If so, it probably represents a fragment of the same, somewhat older and more internal transgressive sequence which was incorporated into a basal thrust sheet shortly after its deposition, before being detached and introduced into the Champsaur Sandstone by submarine gravity sliding in the direction of thrusting. Numerous olistolitic blocks containing nummulites and discocyclinida have recently been identified in the Champsaur Sandstone, within the same depositional basin near Méollion (Lami et al., 1987).

2.2. Age of the Champsaur Sandstone

Dating the Champsaur Sandstone has commonly been a matter of uncertainty on account of the general scarcity of fossils. The few miliolides, nummulites, and plant debris previously found within the sandstone beds were regarded as reworked and hardly conclusive (Beuf, 1959), as are the fragments of discocyclinida and undeterminable foraminifera additionally encountered in this study. Because the Champsaur Sandstone directly overlies deposits attributed to the Priabonian (Fabre and Pairis, 1984; Fabre et al., 1985a, 1985b), which it reworks, they are thought to be Upper Eocene in age (e.g. Moret, 1936a, 1936b; Martini, 1968).

Attempts at separating assemblages from shale horizons revealed occasional microfossils which were determined by R. Wernli. Individual *Globigerina*, microbivalves, microgastropods, *Allomorphina*, and undeterminable Astrorhizidae were encountered in various horizons of the autochtonous unit. One shale parting in the klippe of the Pointe Nord de la Venasque was exceptionally rich, with the following assemblage (sample 90):

Cyclammina sp.
Gyroidinoides sp.
Lenticulina sp.
Lagena sp.

Globigerina officinalis
Globigerinita sp.
Globigerina spp.
Globigerina angiporoides ?
Catasyndrax unicavus ?
Globorotaloides suteri ?
Globigerina praeturrilitina ?
Globigerinatheka subconglobata (?) or Globigerina senni ?

According to R. Wernli, the foraminiferal tests are small, and the assemblage is not homogeneous. It could possibly have been sorted by currents or reworked. Furthermore, the age of this assemblage is doubtful due to the lack of biostratigraphic markers and sufficiently diagnostic associations of species. It can date anywhere from the Upper Mid-Eocene to the Upper Eocene, or possibly younger.

C. Müller kindly determined the following nannoplankton which were taken from various shale partings in the autochtonous unit:

Reticulofenestra umbilica
Cyclococcolithus formosus
Dictyococcites dictyodus
Lanternithus minutus
Coccolithus pelagicus
Sphenolithus moriformis
Cyclicargolithus floridanus
Chiasmolithus sp.
Discoaster barbadiensis,

in addition to individual reworked species of the Cretaceous, Upper Paleocene, and Lower Eocene. Due to the deficiency in species, it was equally difficult to determine the age accurately. It can possibly be assigned to the uppermost Eocene, probably nannoplankton zone NP 18, or younger.

Regrettably, the shale is totally devoid of palynomorphs.

Even though the ages of these fossil findings are doubtful, they agree well with the Eocene/Oligocene boundary generally assumed for most of the flysch successions rich in andesitic rock material along the alpine arc (Vuagnat, 1952) (fig. 2). Unfortunately, it cannot be confirmed with certainty whether the Champsaur Sandstone is lowermost Oligocene in age, as was recently demonstrated for the base of the Taveyanne Sandstone of the Haute-Savoie (Lateltin and Müller, 1987); in view of the strong petrographic resemblance with the Taveyanne Sandstone, probably so.

2.3. Basin Analysis of Autochthonous Unit

A comprehensive sedimentological study was carried out in sandstone unit 3. This unit lends itself exceptionally well to a sedimentological study because (1) it is easily accessible; (2) it is almost entirely autochthonous with respect to the Pelvoux Massif and therefore fully preserves its stratigraphic relationships with older units; (3) it is laterally the most extensive of the turbidite successions, approaching 15 km in length and 5 km in width; (4) it is particularly well exposed with impressive cliffs, displaying the entire stratigraphic sequence above the timber line without major interruptions; (5) it is one of the least deformed of the sandstone units, in a generally normal, upright, nearly horizontal position in which the beds mostly dip less than 30°; and (6) because it is the thickest of the turbidite successions, with sections exceeding 650 m.

2.3.1. Analytical Methods

The following study is based on 12 stratigraphic sections which were measured in the flysch succession of the autochtonous unit, beginning mostly at the non-erosional unconformity with the underlying Schistes à Globigérines and Calcaires à Nummulites Formations. They were continued upwards until a major tectonic contact or inaccessible terrain was reached, or to a point where the sections terminate naturally by a topographic summit or ridge. Eight of these were measured bed-by-bed because initially it was not known whether individual beds could be correlated laterally between adjacent stratigraphic levels. Figure 6 illustrates the method by which these sections were recorded in detail.

Figure 7 shows the distribution of the measured stratigraphic sequences, the spacing of which is in the range of a few hundred meters to over one thousand meters. The arrangement was gradually established as the work went along in the field, depending mostly on the accessibility of the covered terrain. Unfortunately, the survey could not be continued farther to the east. After three attempts, the slope to the NE of the Prouveyrat was found to be too hazardous to climb alone

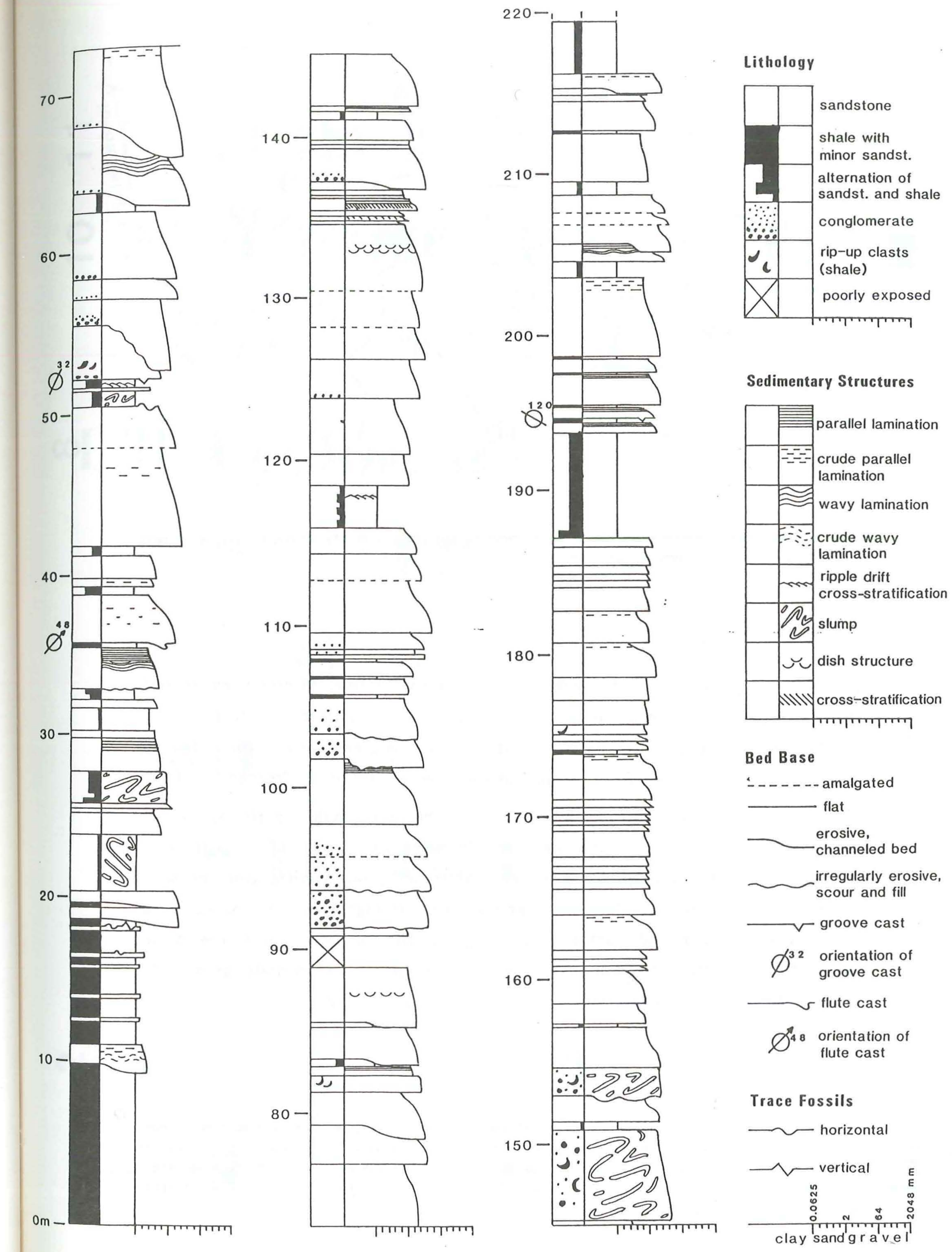


Fig. 6. Representative stratigraphic column of the Champsaur Sandstone illustrating detailed lithological and sedimentary features in its first 220 m above the underlying Schistes à Globigérines Formation in the Combes Roranches. The same stratigraphic section (column no. 11) is reproduced in simplified form in figure 8; its exact location is shown in figure 7.

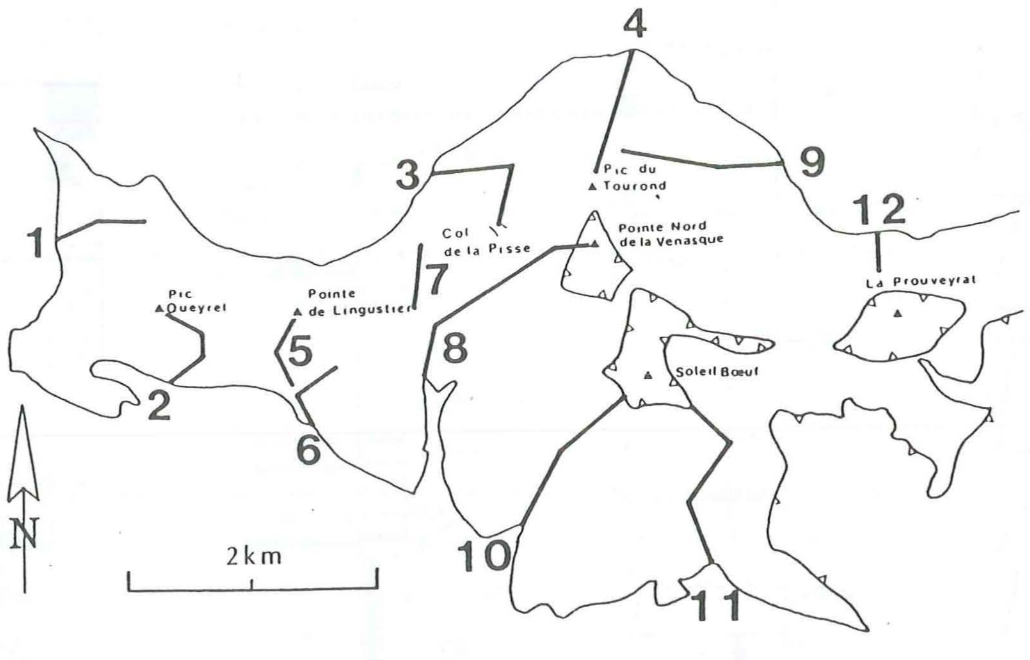


Fig. 7. Outline of western portion of autochthonous sandstone unit (3a), with locations of measured stratigraphic columns depicted in figure 8.

along the length of Tourond Creek. Still farther to the east, Méollion Valley was also inappropriate on account of its rugged countryside and intense folding.

Due to the lack of key beds, the stratigraphic sequences were correlated by visual comparison in the field. Shale horizons, which are easily recognized from afar, were particularly useful in establishing the stratigraphic positions of the columns in relation to adjacent columns. In some cases, individual beds were traced laterally into a neighboring column. Afterwards, the detailed columns were converted to simplified columnar diagrams, then arranged equally spaced in a down-slope direction and numbered accordingly. This is shown in figure 8, in which the correlated stratigraphic columns are aligned approximately at a right angle to the regional paleocurrent direction (away from the reader).

Fig. 8. Correlated stratigraphic columns of sandstone unit 3 aligned equally spaced downslope, i.e. approximately NW-SE. Predominant paleocurrent direction is away from reader. Locations of measured profiles are shown in figure 7. Due to the absence of key beds, a datum plane was arbitrarily chosen and used to prepare the isopach map which is illustrated in fig. 9. For further explanation, see text.

2.3.2. Lateral and Vertical Variability

Between stratigraphic columns approximately 1000 m apart, it was virtually impossible to correlate individual turbidite beds with certainty. This was still a difficult task when, in a trial, the sections were separated by a mere 200 m. Differences between superimposed beds are mostly too subtle in terms of grain size, thickness, internal structure, and composition to allow an easy distinction of one bed from others. Bed-by-bed correlation was further aggravated by amalgation and rapid lateral variations between one column and the other.

Though, presumably, the lateral continuity of some of the coarser and thicker beds approaches the dimensions of the investigated area, individual beds, which at one point were approximately 50 cm thick, were often seen pinching out over a distance as short as 50 - 100 m perpendicular to the general direction of flow, which was from SW to NE (fig. 9). It is therefore believed that few beds are laterally persistent for more than a few kilometers, despite the fact that it was never possible to verify this by tracing individual beds over such a long distance in the field. Another indication is given by the sequence of measured sections (fig. 8) in which, eventually, most of the main facies types (gravelly, sandy, and muddy turbidites) mutually pass into each other. The irregular distribution of sandy and pebbly turbidites is, in some places, readily observed in the field. Similarly, slumping is apparently due to bed failure of only local lateral extent (fig. 8).

The rapid variation in facies and thickness of individual turbidite deposits depends in all likelihood on the characteristics of the flow itself, as well as on the local relief caused by earlier flows. Much is presumably due to the rapid changes inherent in the nature of proximal, high-density, concentrated, turbulent flows which quickly drop the coarsest load and gradually deposit finer-grained sediment over a range of waning flow conditions perpendicular and parallel to the direction of flow. Gentle mounds caused by irregular sediment accumulations on the sea floor are inclined to deviate and confine subsequent gravity flows, leading notably to fluctuations in the thickness of the deposits. This tends to level out morphological features, such as those caused by major slump and debris-flow deposits, depositional lobes, or individual, thick-bedded turbidite beds.

Throughout the turbidite succession there are a number of thinning- and thickening-upward sequences in which the vertical range commonly does not exceed 5 m (fig. 8). This is indicative of some minor channeling, progradation, and lateral migration of rudimentary depositional lobes. Locally, fine-grained, silty turbidite deposits may progressively thin and disappear over a distance of only 10 m. It is thought that these sediments represent overbank deposits that were spilled over topographic irregularities by larger turbidity currents travelling farther downslope.

Unfortunately, the autochthonous flysch unit is exposed only 4 km at its widest section aligned parallel to the general paleocurrent direction (fig. 9), which was invariably to the NE in most, if not all of the sandstone units (Perriaux and Uselle, 1968). The result is that it was not possible to document orderly down-current changes, such as a systematic decrease in the sand-shale ratio, successive appearances or disappearances of Bouma divisions, and the like. Similarly, it was not possible to identify any large-scale, systematic vertical variations in the sedimentary sequences, not even in grain size directly under the thrust plane of the Klippe de Soleil Boeuf and Pointe Nord de la Venasque, suggesting that the sandstones are genetically unrelated to these units, having been introduced axially into the basin from another, more distal source. Areally extensive differences are mostly in the relative proportions of gravelly, sandy, silty, and muddy turbidites, however without any apparent order.

2.3.3. Topography of the Basin Floor

As anticipated from earlier sedimentological studies elsewhere along the alpine arc (Apps and Ghibaudo, 1985; Jean, 1985; Lateltin and Müller, 1987; Lateltin, 1988; Martini, 1968, fig. 3), the Champsaur turbidites are inferred to have longitudinally filled an elongate structural depression. Figure 8 illustrates the manner in which increasingly younger and higher beds successively terminate against a slope by onlap (see also fig. 10).

In order to illustrate the topography of the confining basin, an isopachous map was constructed using the measured stratigraphic sections. Since laterally extensive marker horizons are lacking, it was necessary to select a stratigraphic level for reference. The datum plane was arbitrarily chosen so that it approximately intersects the highest (fig. 8) and westernmost (fig. 9) trace of the onlap surface. The numerical value for each known thickness under the reference plane was first plotted at its respective location on the map using the starting point of each measured stratigraphic section. The isopachs were subsequently determined by conventional mechanical contouring. The stratigraphic sections that were not measured starting at the unconformity with the underlying Schistes à Globigérines and Calcaire Nummulitique Formations were disregarded. Column no. 8 was also excluded from the isopachous map because synsedimentary thrusting in the subsurface has apparently displaced the basin floor relative to its original position.

However, by the deviation of data point no. 8 from the regional pattern, the vertical component of displacement along this fault can be estimated at approximately 40 m.

It turns out that the confining slope consists of a uniform, essentially planar surface dipping gently to the SE. As determined from the trend and spacing of the isopachs, the slightly undulating surface strikes approximately N45°E and is inclined at an angle of 2 - 7° with respect to the horizontal. Field observations confirm that the regional pattern of dip is maintained farther to the east, at least to the valley formed by the northern tributary of the Drac, or "Drac Blanc" as it is called. Considering that a similarly inclined onlap surface has recently been disclosed in the same sandstone unit immediately to the east of the Drac Blanc (Lami et al., 1987), there is little doubt that the sloping surface continues all the way through to Méollion. The total amount of strata required to fill this topographic depression comprises 650 m. Originally, the amount of turbidite fill might have been substantially greater if one considers the stratigraphy to the NW of the investigated area that has since been eroded. For instance, in the lateral equivalents of the southern French Alps, similar structural depressions are known to be filled with nearly 3000 m of sediment (Apps and Ghibaudo, 1985).

The regular and progressive termination of individual turbidite beds against the underlying Schistes à Globigérines Formation is also apparent in unit I (fig. 10). Here, field measurements indicate that, after rotating the turbidites back to their horizontal position by 14°, the slope was originally inclined approximately 12° to the N and striking E-W.

The most probable cause for widespread tilting of the basin floor prior to the accumulation of the turbidite succession is by differential subsidence of the foreland in response to thrust loading, either by synsedimentary, normal faulting (see Fabre et al., 1985a, 1985b; Pfiffner, 1986; Lami et al., 1987; Lateltin and Müller, 1987) or simple flexural downbending (see Beaumont, 1981), or both. Notwithstanding that in the foreland of the Alps extensive fault-bounded structural depressions were locally established in the Paleogene, it is uncertain why synsedimentary normal faulting occurred during an episode of contineta1 *convergence*. If the relative motion between the converging plates were strongly oblique, block-and-basin topography might have been formed by a network of transcurrent faults in continental crust, similar to the Continental Borderland Province off southern California, which contains numerous basins that developed along a system of anastomosing, subparallel faults within the tectonic regime of the San Andreas Fault (Crowell, 1974). On the other hand, it is conceivable that an axis of tension and elongate grabens or half-grabens were formed where the

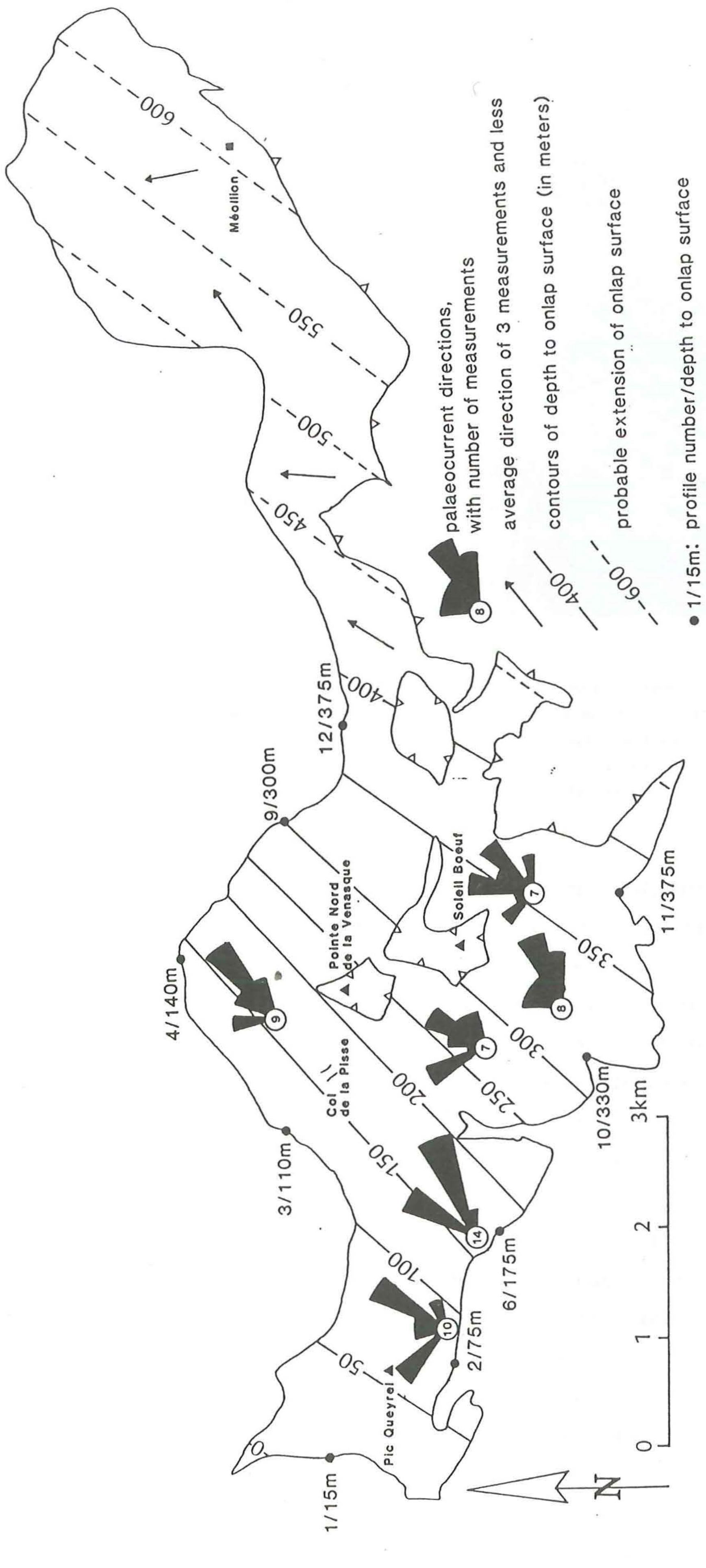


Fig. 9. Paleocurrent- and isopach map of the Champsaur Sandstone illustrating confinement of paleocurrents by uniformly sloping basin floor in autochthonous unit. Isopachs refer to thicknesses below an arbitrarily chosen reference plane (shown in fig. 8); the strata are bounded below by an inclined non-erosional unconformity with the underlying Schistes à Globigérines and/or Calcaires à Nummulites Formations which they onlap toward the NW.

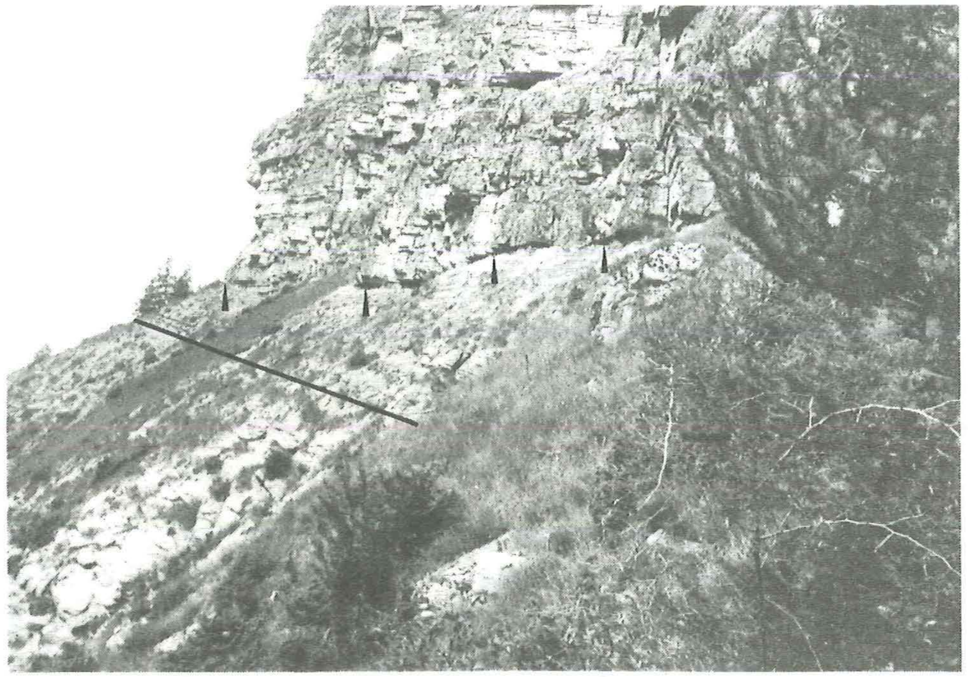


Fig. 10. Onlap of the Champsaur Sandstone (above) onto the Schistes à Globigérines Formation (below) in sandstone unit I. The angular unconformity is denoted by arrows. The attitude of bedding in underlying Schistes à Globigérines Formation is indicated by solid line. Outcrop a few tens of meters above the Route d'Orcières, about 1 km to the SW of the bridge that crosses the Drac Blanc, close to the tributary of the Drac Noir (X=910.5; Y=271.5).

downgoing lithospheric slab was suddenly bent by the load of the adjacent nappes, much like the graben-like structures and associated extensional zones discovered by fault-plane solutions in the axes of modern deep-sea trenches (Isacks et al., 1968). In that the initiation of normal faulting immediately predated or coincided with the appearance of andesites, the generation of which must have been related to a strong compressive resultant between the converging plates, it is possible that fracturing occurred in response to the higher strain rate that might have suddenly been imparted at shallow structural levels on the down-going slab, by the forward surge of the overlying nappes. Though both in the Champsaur and Devoluy synsedimentary normal faulting was apparently locally active during the deposition of the lower nummulitic sequence (Fabre et al., 1985a, 1985b), no such faults have as yet been detected that could account for the depression in question (Lami et al., 1987), which requires differential subsidence of at least 650 m. It is therefore reasonable to assume that, just before the deposition of sandstone units 1 and 3, regional tilting of the sea floor towards the orogenic belt occurred by thrust loading (see Beaumont, 1981). If this assumption is correct, then the Champsaur

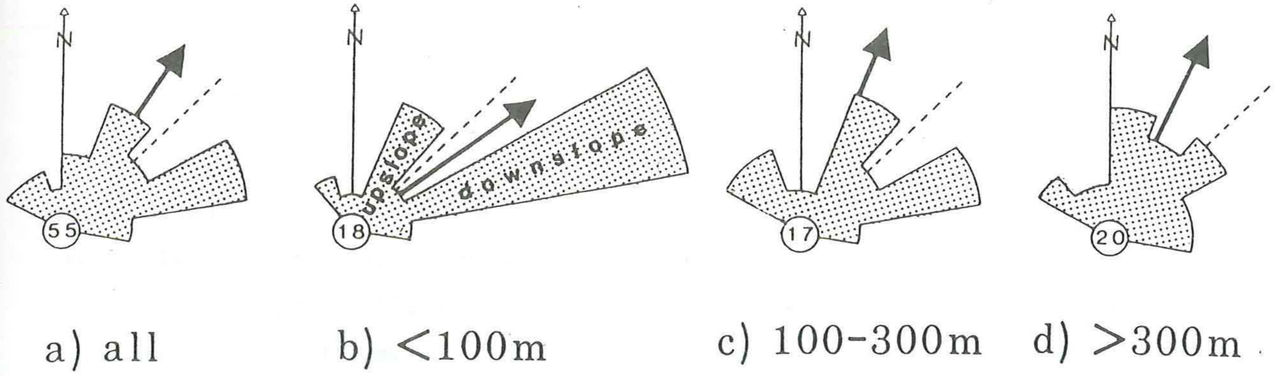


Fig. 11. Circular histograms for directional data of paleocurrents measured in autochthonous sandstone unit for which the exact stratigraphic level above former sea floor is known (see figure 8). Heavy arrow indicates arithmetic mean for a given set of data (N32°E for a; N52°E for b; N21°E for c; and N25°E for d). Dashed line is parallel to strike (N45°E) of confining slope (see fig. 9). For explanation, see text.

basin must have initially been subjected to the load of the adjacent migrating fold- and thrust belt in the Late Eocene, prior to its definitive burial in the Early Oligocene. This agrees well with the date assumed for the emplacement of the lower Embrunais-Ubaye Nappes in the Early Oligocene but falls substantially short of the Miocene emplacement assumed for the higher Parpaillon Nappe (Kerckhove, 1975).

Whatever the cause, it is not clear why the orientation of onlap surfaces differs from what one would ordinarily expect along a N-S trending segment of the Alps: ideally, elongate structural depressions would be aligned N-S as well, with their inclined margins dipping due east or west. This is perhaps an indication that subsequent tectonic transport in the direction of thrusting entailed rotation of units 1 and 3, together with the crystalline basement of Pelvoux to which the latter is fully attached. Alternatively, the confining surfaces possibly comprise partial segments at the extremities of much larger, oblong, elliptical depressions, where portions may trend oblique to the linear regional pattern of the fold- and thrust belt (see Apps and Ghibaudo, 1985, fig. 2.15; and Jean, 1985, fig. 50).

Despite the numerous intercalations of chaotic deposits (see fig. 8), few contain clear-cut slump folds with axes discernible in three dimensions. However, the occurrences that do retain some preferred orientation seem to indicate an alignment in the same sense as the underlying onlap surface. Since there is no apparent association of chaotic deposits with the latter, it is hardly possible that some of these deposits were partially draped over this inclined surface prior to failure and mass movement downslope. More likely, a gentle slope was constantly maintained throughout the basin by synsedimentary thrust loading or folding. However, topographic irregularities might also have been formed by irregular sediment accumulations on the sea floor (sections 2.3.2 and 2.3.5).

2.3.4. Sediment Dispersal Pattern

In the autochthonous flysch unit, a total of 64 primary directional current structures were measured on the underside of turbidite beds in the field. The precise stratigraphic level above the former sea floor is additionally known for 55 of these, which were determined in the course of measuring the 12 stratigraphic columns shown in figure 8. Directional current structures occurring inside individual beds were not recorded because of the difficulty in determining the paleocurrent direction accurately; but they were particularly useful in confirming the overall directional sense of the numerous, mostly linear structures found at the base of beds.

Figure 9 portrays the areal distribution of directional data after the measurements were rotated back to their original horizontal position in the field. Frequency distributions in the 12 stratigraphic sections were plotted in circular histograms, where class frequency is equal to the radius of a given circle segment, not the area. It can be seen that the turbidity currents originated from a multitude of sources, the entire directional spread covering an angle of at least 160°, between N60°W and N100°E. In accordance with a longitudinal infill of a linear depression, the preferred orientation is subparallel to the slope. Throughout all the sandstone units in the area between the Col de la Pisse, Prapic, and Dourmillouse, sands and gravels were predominantly dispersed from the SW towards the NE (Perriaux and Uselle, 1968).

From the arithmetic mean of the paleocurrent directions that were measured in sandstone unit 3, it would normally seem that the average turbidity current flowed N32°E. This does not, however, consider the controls exerted by the topography of the basin floor. In order to illustrate the effects of basin confinement, the directional data of figure 8 was subdivided into three stratigraphic levels above and parallel to the inclined slope. Figure 11 depicts the frequency distributions of the sum of measurements taken along the length and width of (1) the first 100 m directly above the slope, (2) the next 200 m, and (3) all strata higher than 300 m above the confining slope. It appears that the topography was most readily felt by the turbidites immediately overlying the original basin floor, that is, at the basin margin where the flows were laterally confined and deviated by the slope. On average, as one approaches the basin floor in a given vertical succession, the spread of readings tends to gets increasingly tighter in a direction aligned subparallel to the slope. Apparently, the topographic control was negligible above 100 m of the sea floor, i.e. towards the center of the basin, where the turbidity currents were permitted to flow freely on a flat sea floor. The N23°E average of these unobstructed flows is therefore believed to reflect the paleocurrent direction from the original source more accurately. This means that the average turbidity current hit the slope at an angle of 22° with respect to the N45°E strike of the slope. The stongly bimodal distribution in the lowermost parts of the turbidite succession (fig. 11b) is interpreted to represent symmetrical limbs of hyperbolic, low-angle trajectories up and down the deflecting slope.

Fig. 12. Former channel margin and channel-fill deposits in sandstone unit 3a, as seen from footpath leading north to the Col de la Pisse, looking SW. Erosive contact of channel floor is delineated by arrows. Paleocurrent direction is toward the reader. The eastern slope of the Pointe de Lingustier is in upper right corner of photograph.

Approximately 300 m SE of the Pointe de Lingustier, around 220 m above the former sea floor, a large submarine channel was incised more than ten meters into a thick shale horizon (fig. 12). After serving as a major conduit for turbidity currents travelling farther downslope, it was subsequently plugged by channel-fill sandstones and pebbly sandstones. By the intersection of one visible channel margin with both sides of the gully formed by the Ravin du Renc, its orientation can be estimated at approximately N45°E. This direction is roughly consistent with that of the general dispersal pattern determined above from small-scale sedimentary structures. Numerous smaller "channels" that were incised one or more meters into the underlying bed or beds were intermittently encountered throughout the same sandstone unit (see e.g. fig. 6; and plate 4-photo 2, and plate 5-photo 3 by Beuf, 1959).

2.3.5 Depositional Environment

The analyzed sandstone unit comprises an irregular association of the following turbidite facies that have been reviewed by Walker and Mutti (1973). The coarse-grained deposits that mostly correspond to facies A have been differentiated as "predominantly sandstone and conglomerate with minor shale partings" in figure 8. It usually constitutes a limited sequence in which thick-bedded, laterally discontinuous, organized conglomerates (facies A2) and, especially, organized pebbly sandstones (facies A4) dominate. Grading is commonly developed, every now and then with crude horizontal or wavy stratification towards the top of the bed. The base of the bed is often either channeled or irregularly scoured but may also be flat. Though these deposits also occur in their hypothetical channel-fill environment (fig. 12), it is felt that the vast majority of these deposits were dispersed as unconfined, gentle mounds on the sea floor, where the sediment gravity flows quickly dropped their coarsest load.

Deposits belonging mostly to facies B (medium to coarse sandstone) and C (classical turbidites) are distinguished as "predominantly massive sandstone beds with minor shale partings" in figure 8. With increasing grain size and erosive power, however, facies B may grade into or be associated with facies A4. Similarly, especially in sequences consisting of a "predominantly thin-bedded alternation of sandstone and shale" (fig. 8), facies C may grade into or be interbedded with the more distal deposits described below. The massive sandstones may occur with (facies B1) or without (facies B2) dish structure. The beds belonging to facies B1 display a high degree of basal erosion and result from the rapid deposition of concentrated, high-density gravitiy flows close to their source (see Lowe, 1982). Because this facies apparently cannot be ascribed to well developed channel systems, it is thought that these beds were deposited close to the main axes of largely unconfined flows, adjacent to and down-current from facies A4. Facies B2 essentially consists of a sequence of welded Bouma A divisions in which scoured and channeled beds may also occur, but less so. These deposits were presumably laid down at a slightly greater distance from the loci of the same flows. Beyond this setting, the character of these deposits might have gotten increasingly more depositional and, with the gradual emergence of shale partings and truncated basal Bouma divisions, facies B2 might have progressively given way to facies C. These deposits comprise the classical proximale turbidites that were in all likelihood deposited on mostly unchanneled mid-fan-like depositional lobes.

The sequences consisting of "predominantly shale with minor sandstone beds" (fig. 8) mostly correspond to one or more of the facies differentiated as D, E, and G. Facies D refers to depositional successions in which classical distal turbidites (characterized by base-cut-out Bouma sequences) prevail. It is thought that the greater part of the beds belonging to this facies were deposited on the lower fan or basin plain. Facies E differs from facies D in that it has a higher sand/shale ratio; furthermore the beds are generally thinner and more irregular and discontinuous than in facies D. Most of these deposits were laterally spilled over topographic irregularities - not levees but irregular sediment accumulations caused by earlier flows (cf. Walker and Mutti, 1973) - by larger turbidity currents travelling farther downslope. Facies G results from the intermittent deposition of low-density turbidity currents of low velocities transporting clay- and silt sized particles in low concentrations, accompanied by slow, hemipelagic settling through the water column on the lower fan-like areas and basin plain.

Facies F is intended to denote all deposits that have been appreciably affected by downslope mass movements after deposition, and is assumed by Walker and Mutti (1973) to occur on the slope and in the inner fan region. In the Champsaur Sandstone, restricted slumps may occur in virtually any turbidite facies and throughout the entire depositional basin (fig. 8). This means that slumping of individual turbidite beds is not necessarily indicative of the slope that delimits the inner margin of the basin, particularly where it is not associated with pelagic or hemipelagic sediments. In the Champsaur Sandstone, slumping is mainly related to penecontemporaneous liquification by rapid deposition (section 2.1.2.), whereby downslope mass movements occured in response to either irregular depositional morphology or a gentle inclination of the sea floor by synsedimentary thrust loading (section 2.3.3.). Similarly, the nummulitic olistolites that were introduced by gravity deposition cannot be assigned to a specific slope environment, though their presence does suggest that the inner slope leading into the basin cannot have been particularly remote from their final site of deposition.

From the mutual relationships between adjacent stratigraphic columns (fig. 8), it is evident that the main turbidite facies must gradually pass into each other laterally, generally within a distance of only a few kilometers. The ideal downcurrent facies sequence deposited by a single, hypothetical sediment gravity flow in the Champsaur is therefore thought to have essentially been A2 - A4 - B1 - B2 - C - D - G, whereby facies E (and presumably some D) were locally spilled over depositional mounds by larger turbidity currents in transit. The successive downcurrent depositional environments along the full length of the flows would normally seem to have encompassed a region between the inner fan or channelled mid-fan and the basin plain. However, it is extremely difficult to place the findings of this study into the generalized facies scheme of a single submarine fan system. Rather, it is felt that the vast majority of sediment gravity flows were introduced laterally into the basin from its inner flank, by an array of *several* sources along the deformation front of the fold- and thrust belt. The depositional geometry of major sediment accumulations is inferred to have been very similar to those reported by Surlyk (1984) for a coalescent fringe of submarine fans along a major fault scarp on tilted blocks. Several lines of evidence, most of which are analogous to Surlyk's observations, suggest that the flows cannot have emanated from a single point of origin at a fan apex:

1) Vigorous scouring, pebbly sandstones, and conglomerates occur sporadically throughout virtually the entire width, length, and depth of the turbidite succession, suggesting that high-velocity currents were intermittently introduced to all sectors of the depositional basin.

2) Despite this erosive power, there is a deficiency of real channels, the initiation and maintenance of which would require a *stationary* locus of high-velocity flows. Apart from the only true channel near Pic Queyrel (fig. 12), and a much smaller one in the valley of Méollion (see plate 4/photo 2 by Beuf, 1959), basal erosion is generally restricted to individual flows, which may locally scour the underlying bed or beds to a depth of one or several meters. It is sensed that, in the absence of a main feeder channel, the potential erosive energy of these flows would never have been greatly confined and therefore quickly dissipated over a large surface.

3) There is a relatively large directional spread of paleocurrent indicators over any given vertical section of the sea floor (fig. 9), particularly at a safe distance from the confining slope (fig. 11).

4) The lack of meaningful lithofacies patterns and the uncharacteristic rapidity of vertical and lateral facies changes throughout virtually the entire investigated area seem to reflect the lateral mergence of rudimentary depositional lobes and extensive interweaving of sediments derived from both proximal and distal sources. In such a situation, gentle mounds caused by irregular sediment accumulations would tend to deviate and confine subsequent gravity flows, leading to abrupt lateral facies variations and fluctuations in the thickness of the deposits (section 2.3.2.).

2.3.6. Estimation of Depth and Width of Basin

Whereas in any given vertical section the lower nummulitic transgressive sequence was invariably deposited on the *external* side of the migrating basin, one may assume the the ensuing structural depression was - for the most part - subsequently filled by turbidites derived from *internal* terrains (chapter 5). Thus a discrete angular unconformity commonly separates two stratigraphic entities that were in all likelihood derived from opposite shores of one and the same basin, the Nummulitic Sea. In view of this peculiar circumstance, it is thought that the migrating foreland trough cannot at any one point have been particularly wide or deep, all the more so towards the more external zones of the Alps (section 1.1.).

In that the Champsaur Sandstone progrades directly onto the Schistes à Globigérines and/or Calcaires à Nummulites Formations deposited in shallow water close to the opposite shore, a feeling for the width of the basin may be obtained by estimating the distance travelled by the sediment gravity flows from their source. In section 2.3.2. it was concluded that few turbidite beds are laterally continuous for more than a few kilometers, and that the greater part of facies cannot be traced laterally to any large extent. Even in a downcurrent direction, the facies changes between successive stratgraphic columns are generally so rapid (compare figures 7 and 8) that one may infer that the continuity of individual deposits cannot have greatly exceeded the width of the investigated portion of the basin, which is 4 km at its widest section aligned parallel to the general paleocurrent direction. However, the distance traversed by the sediment-laiden currents must have been at least 15 km from their assumed source under the Embrunais-Ubaye Nappes, probably more (see chapter 5, especially section 5.4.). Considering that the Schistes à Globigérines and Calcaires à Nummulites Formations were depositied within, say, 5 km of the opposite shore, the total width of the basin must have been at least 20 km from coast to coast, if not more.

In terms of depositional environment, the volcaniclastic members of the Champsaur Sandstone are transitional between the "Molasse verte" and "Molasse Rouge" of the St. Didier Sandstone in the west and traditional turbidites deposited in deeper water to the east. Sandstone unit 3 embodies the very last "flysch" that was deposited during the alpine orogeny in this part of the dwindling Tethys. Here, the turbidite basin was presumably somewhat narrower and shallower than during the deposition of the more internal units and their lateral equivalents (Annot Sandstone, Flysch des Aiguilles d'Arves, and Ultrahelvetic Sandstone). In fact, the uncharacteristic deficiency of lateral continuity in the Champsaur

Sandstone might be partially due to the reduced depth of the basin and, therefore, the potential energy available for the acceleration of sediment gravity flows downslope. It is perhaps no coincidence that much the same situation should occur in another, similarly restricted turbidite basin estimated to have been only 1 km deep (Surlyk, 1984). By contrast, the lateral continuity of conglomeratic marker horizons may easily exceed 10 km in the Annot Sandstone (Jean, 1985; Apps and Guibaudo, 1985), indicating higher velocities that perhaps reflect a greater basin depth.

In view of the fact that the migrating foredeep evolved into a partly continental "Molasse" facies only 14 km to the west, the uppermost turbidite beds in figure 8 must have been deposited close to but below the storm wave base, which might have been uncharacteristically shallow in comparison to earlier basins, due to the reduced fetch. In that even the lowermost shale breaks - which lie only a few tens of meters above the erosional unconformity of the lower nummulitic transgressive sequence - lack wave reworking as well, subsidence to depths below the storm wave base by thrust loading might have been rapid, or, conversely, postponement of the turbidite fill long. As is ordinarily the case for the greater part of the curvilinear turbidite belt (W. Wildi, pers. comm.), it is felt that the massive introduction of terrigeneous clastics was deferred for a certain time period after the initial downwarp of the sea floor. Assuming that the former depression was filled more or less suddenly without appreciable synsedimentary subsidence, it follows that the basin floor was initially at least 900 m deep at its deepest part near Méollion (see figures 8 and 9). Assuming that the St. Didier Sandstone was deposited at or near sea level 28 km to the west of Méollion, as a first approximation one may estimate that, for every kilometer the migrating depositional center traversed in the direction of thrusting, it became 32 m less deep.

Since this variation is in the same sense and order of magnitude as the inclination of the onlap surface determined at the base of the Champsaur Sandstone (fig. 9), at first thought it would seem that the basin floor might have risen continuously to the west, all the way through to the region of Devoluy. However, it is impossible that the St. Didier Sandstone was deposited close to the basin margin in the same, that is,"unmigrated" basin as that of the Champsaur Sandstone, because in that case the rock materials contained in the St. Didier Sandstone would have to have been introduced laterally into the basin from the *west*. This is hardly possible considering that neither ophiolites nor Hercynian crystalline massifs are currently exposed on the external side of the Devoluy basin remnant (sections 5.2. and 5.4.).

2.5. Conclusions

The Champsaur Sandstone was derived from the inner basin margin (chapter 5), close to the deformation front of the fold- and thrust belt. The sediment gravitiy flows were quickly diverted to the NE and laterally confined by the foredeep. In that they originated from a multitude of sources, the depositional environment cannot have been that of a classical submarine fan system, much less a deep-sea fan. In relation to older and more internal units, the Champsaur basin was comparatively narrow and shallow, whereby the depth at which the very last turbidite beds were deposited cannot have greatly exceeded that of the storm wave base.

The sedimentological evolution of the Champsaur Sandstone is nevertheless similar to those reported for other Late Eocene or Early Oligocene basin onlap fills in the Central and Western Alps. They accumulated in a restricted structural depression that was in all likelihood elongate and originally aligned parallel to the orogenic belt. The general direction of transport to the NE in most, if not all of the Champsaur units (Perriaux and Uselle, 1968) conforms with the overall longitudinal, arcuate fill of the foredeep, which is apparently prevalently unidirectional along most of the alpine arc, apart from supply transverse to the basins, such as in the Flysch des Aiguilles d'Arves (see Deharveng et al., 1987). In the Champsaur Sandstone, the direction of sediment transport to the NE is intermediate in the gradual change of course from the largely northerly direction in the Annot Sandstone of the southern French Alps (Bouma, 1962; Stanley and Mutti, 1968; Apps and Ghibaudo, 1985) to the extensive easterly direction in the Taveyanne Sandstone and related rocks of the western Swiss Alps (see Radomski, 1961; Martini, 1968; Sawatzki, 1975; Lateltin, 1988). Since a direct link through continuous turbidite beds can be ruled out, it remains obscure why one direction would be favored over such a long distance, with reversals in the dominant dispersal pattern only in the Flysch des Aiguilles d'Arves (Deharveng et al., 1987), especially in a tectonic environment as active as that of a migrating foreland turbidite belt.

In accordance with the presumed successive evolutionary stages of foreland basins (Beaumont, 1981), after deposition of the initial nummulitic transgressive sequence, subsequent underthrusting, uplift, erosion and redeposition is inferred to have been both widespread and rapid. In analogy to the nummulitic limestone blocks encountered in the Champsaur Sandstone, numerous such blocks and cobbles have been noted in the Taveyanne Sandstone (Martini, 1968; Ducloz, 1944, in Vuagnat, 1952). Cobbles of the Taveyanne Sandstone have, in turn, been described in the slightly younger Val d'Illiez Sandstone (P. Termier, 1981, in Martini, 1968; Sawatzki, 1975).

3. PETROGRAPHY

3.1. Introduction

It has long been recognized that the Champsaur Sandstone corresponds to the Taveyanne Sandstone of the Central Alps, both structurally and petrographically (de Quervain, 1928; Vuagnat, 1947b, 1947c, 1949). These are characterized by their abundance of volcanic rock fragments: mostly andesites with subordinate amounts of ophiolitic material, mostly diabase, plus minor amounts of acid volcanics (Vuagnat, 1952). To the south, petrographically comparable volcaniclastic graywackes are described in the St. Antonin Syncline of the southern French Alps (Alsac et al., 1969; Boucarut and Bodell, 1969), in the Petrignacola Sandstone of the northern Apennins (Elter et al., 1964, 1969), and in the Tusa Facies of southern Italy and Sicily (Ogniben, 1964).

Structurally, the Champsaur Sandstone is closely associated with the St. Didier Sandstone to the west, which is fully accommodated in this petrographic study. It was sampled periodically along the route nationale N 537, between the village of St. Didier and the Col du Festre. The St. Didier Sandstone is petrographically distinguished from the Champsaur Sandtstone mostly by the lack of andesitic rock material and associated decrease in plagioclase grains that coincides with a significant increase in sedimentary clasts and ophioitic material. Due to the greater diversity of its constituents, and the substantial introduction of ophiolitic material at the expense of andesite fragments, the St. Didier Sandstone has been likened to the Val d'Illiez Sandstone of the western Swiss Alps, which occupies a similar, more external position with respect to the Taveyanne Sandstone (Vuagnat, 1947a). Other volcaniclastic sequences characterized by a comparable, significantly lower andesite/ophiolite ratio are known from the southern French Alps, in the Clumanc Sandstone (Chauveau and Lemoine, 1969; Bodelle, 1971; de Graciansky et al., 1971).

The three main types of volcanic rocks encountered in the Champsaur and/or St. Didier Sandstones - andesites, ophiolites (diabase), and acid volcanics - share no genetic relationship. The acid rocks presumably originate from continental volcanic activities at the end of the Variscan era during the Late Paleozoic. Similar postorogenic volcanic rocks are commonly found associated with Variscan basement, such as in the Estérel, Argentera and other external crystalline massifs of the Alps (Baubron, 1984), including the Pelvoux Massif (Vatin-Pérignon et al., 1972). By contrast, the ophiolites are related to the generation of oceanic crust in the Penninic Ocean during the Jurassic and Cretaceous. In the Tertiary clastic sequences of the foreland, the presence of such cobbles - which often retain a subduction-related, high-pressure metamorphic overprint - has been attributed to erosion of higher accreted Penninic units (Vuagnat, 1943; de Graciansky et al., 1971; Sawatzki, 1975). On the other hand, the andesitic rocks are contemporaneous or slightly older than the age of the Champsaur Sandstone, i.e. probably uppermost Eocene in age (Fontignie et al., 1987). They form part of an ancient volcanic arc extending from Sicily and the Apennines to the Central Alps (Stalder, 1979; Vuagnat, 1985). In the course of continental collision, the andesitic volcanoes were either incorporated into one or several nappes and transported to the basin margin in the foreland, away from the Alps (Vuagnat, 1952), or erected closer to the depositional basin in the foreland, in a region neighboring the Ultrahelvetic Zone and lower Penninic nappes.

In addition to the volcanic rocks, the graywackes contain considerable amounts of metamorphic and plutonic rock fragments derived from a mostly granitic basement, presumably the same Variscan basement massif with which the acid volcanics were formerly associated, though not necessarily the massif of Pelvoux (see section 5.1.). In subordinate amounts, the sandstones also include an assortment of sedimentary rock fragments eroded from a range of sedimentary sources, such as the underlying Mesozoic sedimentary cover, the Priabonian sequence, and internal Penninic nappes.

It is not the author's intention to dwell on the petrographic description of each and every discernible type of lithoclast. In that they are sufficiently similar to those described by de Quervain (1928), Vuagnat (1943, 1952), and Sawatzki (1975), any descriptive account going beyond basic comparison would be redundant. Therefore, for additional information, the interested reader is referred to their work. The monograph by Vuagnat (1952), with scores of photographic plates and carefully drafted hand drawings, is particularly useful. The andesitic rock fragments are an exception, since their mineral associations are fundamental to the understanding of metamorphic reactions discussed further on in the text.

3.2. Description of Lithoclasts

3.2.1. Andesites

The Champsaur Sandstone has been thought to include volcanic remnants related directly to eruptions in or near the depositional basin (Termier and Lory, 1895; Bellair, 1957; Beuf et al., 1961; Giraud, 1983). Contrary to this belief, no signs indicative of volcanic activity concurrent with the deposition of the turbidite sequence were observed, such as submarine lava flows, intrusive bodies, pyroclastic fallout deposits in the shale partings, and the like. Where the graywacke is composed almost exclusively of andesitic rock fragments, such claims must result from metamorphic transformations which apparently can mask the clastic nature of the sedimentary rock (Martini and Vuagnat, 1967; Vuagnat, 1985). Like the Taveyanne Sandstone (de Quervain, 1928), the volcanic rock material in the Champsaur Sandstone is entirely epiclastic, derived from erosion of older volcanoes related to previous eruptive episodes. For the most part, they were eroded from solid masses generally lacking vesicular or scoriaceous structure, presumably mostly lava flows, with little, if any, evidence of explosive violence, such as volcanic ash, lapilli, or other ejecta.

In the coarser beds of the autochthonous unit, it is estimated that the total amount of andesitic rock debris may approach 90% of the sedimentary rock. In most of the conglomeratic horizons shown in figure 8, the greater part of the pebbles are composed of these volcanic rocks (fig. 24). Here, the andesites are discernible in hand specimen by bright plagioclase phenocrysts set in the very dark-colored chloritic matrix of the pebbles and cobbles which were more impermeable to solutions precipitating lighter-colored laumontite or calcite throughout the rock.

In both texture and original mineralogical composition, the andesite fragments closely resemble those described by de Quervain (1928), Vuagnat (1952), Martini (1968), and Sawatzki (1975) in the Central Alps; it may safely be assumed that they originated from the same parent rocks. The most common constituent is plagioclase feldspar which is present over a wide range of sizes, from relatively large, phaneritic phenocrysts to tiny laths in the groundmass. Augite and, to a lesser extent, hornblende are the characteristic ferromagnesian minerals. In many rocks, opaque iron ore is an accessory constituent. The originally glassy matrix is completely transformed.

In addition to the basic mineral assemblage outlined above, the andesitic rock displays a variety of secondary minerals associated with burial diagenesis or recrystallization to assemblages transitional between those that commonly characterize zeolite-and prehnite-pumpellyite facies rocks, resulting from subsequent burial metamorphism in the sense of Coombs (1961). Relevant alteration processes are extensive albitization, chloritization, calcitization, and laumontitization coupled with the development of pumpellyite, prehnite and sphene, and minor sericitization. The secondary transformations will be described and discussed in great length later on in the text, in the section devoted to the metamorphism of the andesite-rich, sedimentary rocks.

*Plagioclase.*___The original plagioclase is mostly replaced by albite. Initially, the plagioclase was more calcic, usually in the compositional range of labradorite and, in extreme cases, bytownite (Martini, 1968). The original, more basic plagioclase is occasionally found in some strongly calcitized zones where calcite functioned as a sealant against reactive solutions. Where present, phenocrysts of primary, more calcic plagioclase are easily recognized by their conspicuous compositional zoning and clear, translucent appearance, which is in marked contrast to the customary, uniformily turbid nature in the altered state. On rare occasions, replacement may be progressive and preferential, leading to the presence of more than one plagioclase in the same rock.

Calcic plagioclase is unstable under low-grade metamorphic conditions, and, as a consequence, its replacement is widespread and its alteration products diverse in these rocks. Firstly, it has been transformed to laumontite, pumpellyite, chlorite, and, less commonly, prehnite in close association with secondary albite. The replacement by optically continuous laumontite is either wholesale or partial, and often preferential, largely as a function of grain-size and, hence, porosity and permeability of the rock. Replacement by pumpellyite in clusters of small, rounded pellets is common. Occasionally, individual grains of plagioclase are progressively replaced by single, perforated, skeletal-like crystals or replacement aggregates of prehnite. Calcite may substitute for these calc-silicates as a common alteration product of plagioclase. Zoned inclusions of glass have extensively been transformed to chlorite. In some altered rocks, chlorite pseudomorphs have assumed the characteristic outlines of plagioclase phenocrysts. In addition, minor, scattered grains of sphene, opaques, and micaceous flakes reminiscent of sericite can be present.

*Augite.*___Augite is by far the most common mafic constituent that occurs in the andesitic rocks. In thin section, it is colorless or pale green, and occurs most frequently as phenocrysts which are often twinned and, in some cases, may contain inclusions of plagioclase. It alters readily to coarsely crystalline calcite and lamellar masses of chlorite, and in both cases replacement may develop progressively from cleavage traces and proceed inward until the entire crystal is consumed.

*Hornblende.*___Less commonly, hornblende forms phenocrysts that display conspicuous corrosion rims. In thin section, it is often euhedral and strongly pleochroic in shades of brown and green. Since it is felt that it is *less* prone to metamorphic alteration (cf. de Quervain, 1928), it appears that its subordinate share is primary. Much of the alteration seen in thin section is presumably due to reactions that occurred with the lava during eruption, leading to various degrees of magmatic corrosion. Such reaction rims are of variable width and are typically charged with numerous minerals, notably opaques and sphene.

*Volcanic glass.*___The originally glassy matrix has been completely devitrified by incipient metamorphism. It has mostly recrystallized to chlorite in addition to scattered clusters of cloudy sphene.

3.2.2. Geochemistry of Andesite Cobbles

A total of 10 andesite cobbles were chemically analyzed for their major-element concentrations. All element concentrations were determined in the Department of Mineralogy, University of Geneva, on whole-rock powders with a Philips 1410 x-ray spectrometer, except for ferrous iron which was measured using the colorimetric method by Pratt. The H_2O contents were determined by the Penfield method. The chemical, normative, and modal compositions of the andesite cobbles are shown in tables I, II, and III, respectively.

Samples 1-7 were taken from a locality discovered to be exceptionally rich in abnormally large andesite cobbles, the diameter of which may reach approximately 10 cm. They were sampled in Méollion Valley, directly above the Calcaires à Nummulites Formation, in a thick, gravelly horizon metamorphosed to a facies denoted "vert" (Chapter 6). With regard to whole-rock sampling, this occurrence - the exact location is indicated by stars in figure 3 - is presumably richer in large andesite cobbles, and easier to find, than the one to the east of the Signal de Montorsier that was mentioned by Boussac (1912, p. 150) and sampled by Fontignie et al. (1987). The cobbles of samples 8-10 were found scattered in a coarse-grained sandstone bed metamorphosed to the mottled laumontite facies, approximately 80 m above the onlap surface in stratigraphic column no. 10 (see figure 8).

The sampled andesite cobbles thus stem from two fundamentally different metamorphic facies discussed in detail under the appropriate headings later on in the text. This refers to the metamorphism of the enclosing fine-grained *sediment*, and not necessarily that of the *cobble* itself. Whereas in the mottled facies laumontite, pumpellyite, and prehnite are characteristic of the assemblage, these

Table I. Major-element concentrations of andesite cobbles in autochthonous unit.

	from "vert" facies (Méollion)							from mottled facies		
sample	1	2	3	4	5	6	7	8	9	10
SiO_2	47.22	44.61	53.01	51.58	45.29	46.09	54.54	50.79	50.01	55.01
TiO_2	0.70	0.69	0.53	0.77	0.61	0.97	0.74	0.82	0.87	0.65
Al_2O_3	19.72	18.91	18.08	18.68	17.62	20.96	17.26	17.11	16.86	17.85
Fe_2O_3	2.58	2.45	1.46	4.76	0.94	2.82	2.51	3.99	1.92	2.87
FeO	4.29	4.86	2.90	3.62	3.51	5.20	3.48	6.20	4.46	4.41
MnO	0.07	0.12	0.05	0.07	0.10	0.10	0.10	0.16	0.17	0.12
MgO	2.88	1.52	2.02	4.61	3.15	4.38	4.04	4.71	3.69	3.92
CaO	8.95	11.46	8.90	3.61	14.58	8.74	5.43	3.49	7.95	2.47
Na_2O	3.92	3.44	4.17	5.59	3.10	3.23	4.32	2.74	2.39	3.38
K_2O	2.20	2.59	2.41	1.39	2.26	1.69	3.92	5.32	4.62	6.13
P_2O_5	0.15	0.16	0.24	0.16	0.17	0.28	0.22	0.18	0.22	0.17
H_2O+	3.34	2.62	2.13	3.93	2.45	3.49	2.46	3.73	3.96	2.42
CO_2	3.48	6.06	4.02	1.26	6.09	1.86	1.10	0.63	2.50	0.39
Total	99.50	99.49	99.92	100.10	99.87	99.81	100.12	99.87	99.62	99.79

Table II. CIPW-normative compositions of andesite cobbles in autochthonous unit.

sample	1	2	3	4	5	6	7	8	9	10
Plag (An)	39.24	37.55	32.74	15.83	51.17	52.14	30.61	34.40	51.68	23.28
Quartz	0.00	1.84	7.58	0.00	0.00	0.00	0.00	0.00	0.96	0.00
Orthoclase	13.00	15.31	14.24	8.21	13.36	9.99	23.17	31.44	27.30	36.23
Albite	33.17	29.11	35.29	47.30	26.23	27.33	36.56	23.19	20.22	28.60
Anorthite	21.42	17.50	17.17	8.90	27.49	29.77	16.13	12.16	21.63	8.68
Corundum	3.04	4.03	2.32	4.72	0.00	2.91	0.00	2.39	0.00	2.47
Diopside	0.00	0.00	0.00	0.00	4.26	0.00	1.95	0.00	0.46	0.00
Hypersthene	12.36	10.41	8.37	17.38	5.83	11.72	9.84	12.05	14.45	13.69
Olivine	0.35	0.00	0.00	1.34	3.48	4.26	2.33	7.98	0.00	1.99
Magnetite	3.19	3.18	2.12	3.29	1.36	3.58	3.25	3.36	2.78	3.12
Ilmenite	1.33	1.31	1.01	1.46	1.16	1.84	1.41	1.56	1.65	1.23
Apatite	0.35	0.37	0.56	0.37	0.39	0.65	0.51	0.42	0.51	0.39
Calcite	7.91	13.78	9.14	2.87	13.85	4.23	2.50	1.43	5.69	0.89

Table III. Modal compositions of andesite cobbles in autochthonous unit.

sample	1	2	3	4	5	6	7	8	9	10
Amphibole	---	(---)	---	---	(---)	X	X	---	---	X
Cpx	(---)	---	---	---	X	X	X	X	X	X
Calcite	X	X	X	X	X	X	X	(---)	X	---
Sphene	X	(X)	X	X	X	X	X	X	X	X
Prehnite	?	---	X	---	---	?	---	?	---	---
Pumpellyite	?	---	---	---	---	---	---	(X)	---	(X)
Laumontite	---	---	---	---	---	---	---	?	---	---
Quartz	---	---	X	---	---	---	---	---	---	---
Opaques	X	X	X	X	X	X	X	(X)	X	X
Plagioclase	X	X,z	X,z	X	X,z	X,z	X	X	X	X
Sericite	?	?	?	?	?	?	?	?	?	?
Chlorite	X	(X)	X	X	X	X	X	X	X	X

--- = none; (---) = negligible; (X) = minor; X = major; ? = doubtful; z = zoned

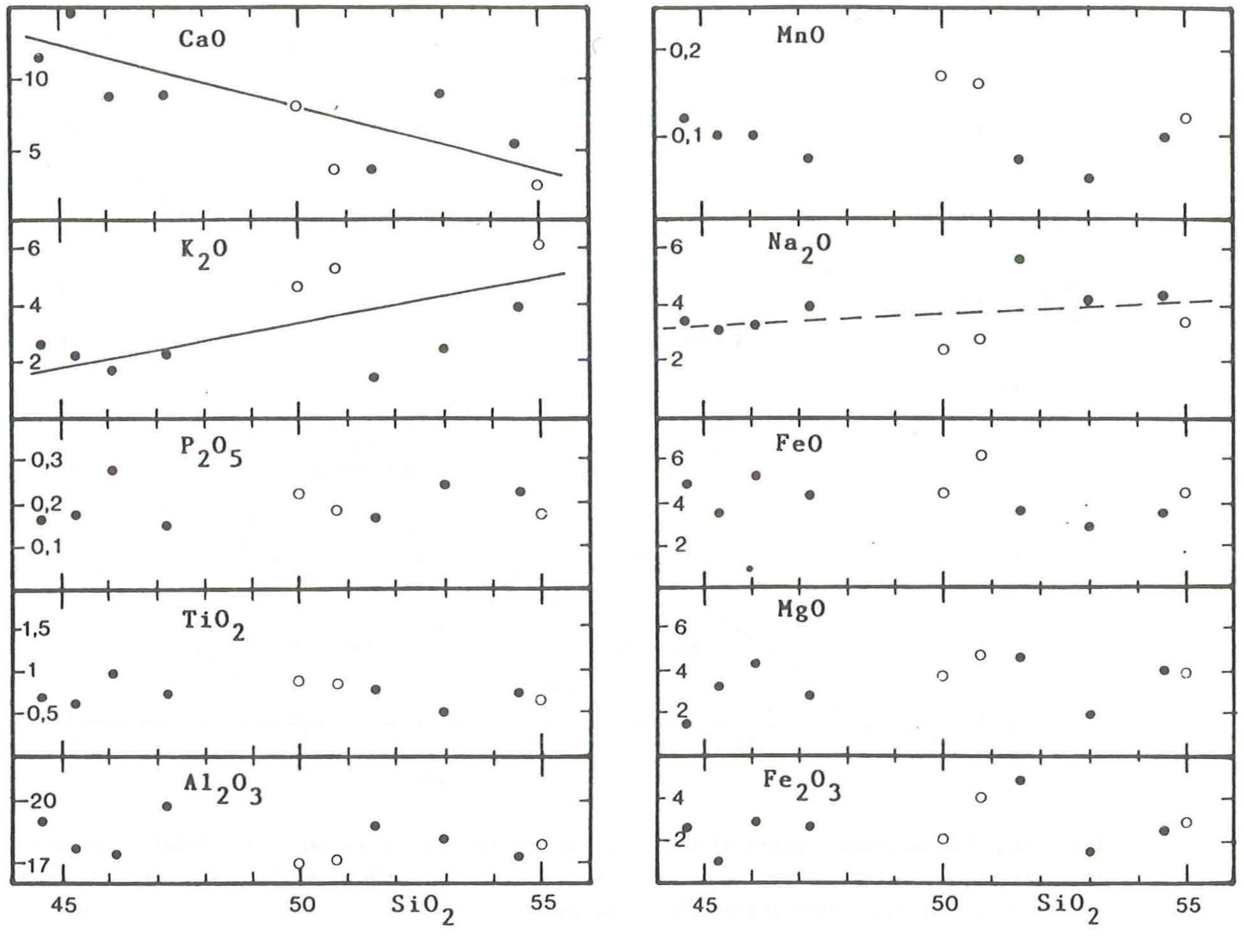


Fig. 13. Major oxides of andesite cobbles (autochthonous unit) plotted against increasing silica. The compositions of cobbles taken from the mottled laumontite facies are indicated by open circles, those from the vert facies by filled circles. The regression lines were adjusted visually. The CIPW-normative and modal compositions of these cobbles are additionally shown in tables II and III, respectively.

are commonly missing in the vert facies because of the early precipitation of calcite which impregnates the rock against subsequent metamorphic solutions and additionally lowers the stability of the calc-silicates by the associated rise in the partial pressure of CO_2. It is interesting to note that the two groups of cobbles are essentially characterized by the same assemblage, though in varying proportions of the minerals, despite the apparent contrast in metamorphism. This is due to the impermeability of the cobbles which, like calcite, seemingly inhibit aqueous solutions that would normally precipitate laumontite, pumpellyite, and prehnite. Albitization, which ordinarily is common to both metamorphic facies, is apparently slightly subdued in the vert facies because of its substantially higher concentration of calcite that acts as an additional sealant. The mottled facies

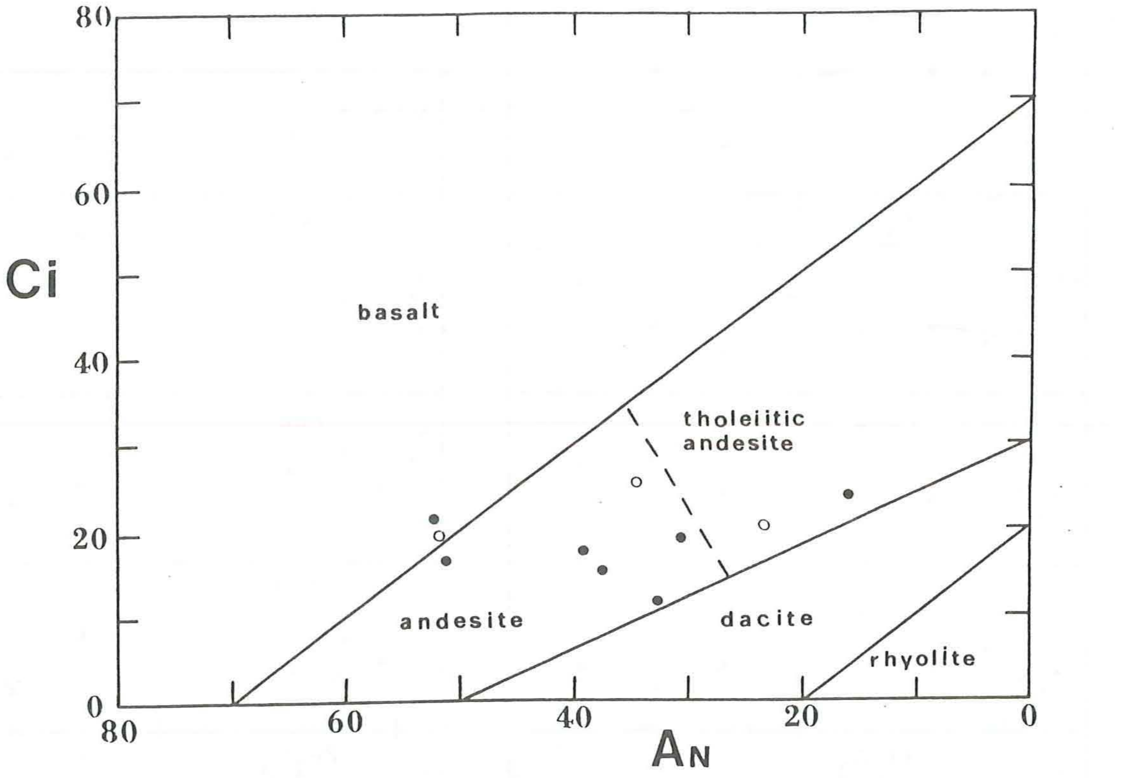


Fig. 14. Compositional plots of andesite cobbles (autochthonous unit) in normative plagioclase composition (An) versus normative color index (Ci) diagram, with classification fields proposed by Irvine and Baragar, 1971 (same symbols as in figure 13).

customarily does not contain calcite; that of sample 8 is present in minute cracks, and sample 9 is transitional to vert.

When the chemical analyses of the two sets of cobbles are compared with one another, the samples taken from the vert facies are on average richer in CaO and CO_2 than those taken from the mottled facies. This is related to the amounts of modal calcite which correlate possitively with both CaO and CO_2. It is not clear why the samples taken from the mottled facies are enriched in SiO_2, K_2O, and MnO, and depleted in Na_2O, with respect to the cobbles samples in the vert facies. Neither can be explained by pervasive albitization, the only other disparity observed in thin section, apart from calcitization.

Nevertheless, the andesite cobbles appear to have been little affected in their bulk chemical composition. The major-element concentrations in the andesite cobbles agree fairly well with those reported by Gill (1981) for basaltic, high-K, orogenic andesites, though some samples appear somewhat depleted in silica, while others are too enriched in potash, even for high-K andesites. Even though, at first thought, it would appear that calcite has fully invaded most of the rocks, even

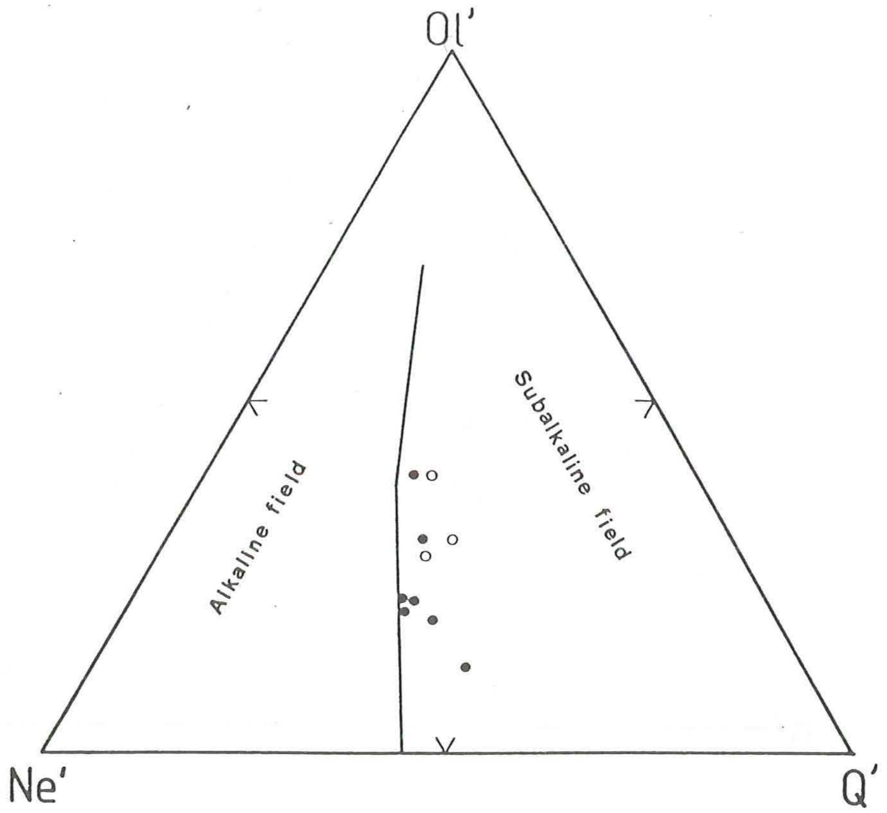


Fig. 15. Compositional plots of andesite cobbles (autochthonous unit) in Ol'-Ne'-Q'projection defined by Irvine and Baragar, 1971 (same symbols as in figure 13).

CaO, when averaged, lies surprisingly well within the compositional range of typical andesites. This suggests that a portion of metasomatic CaO needed to form calcite in the cobbles was released from clinopyroxene or calcic plagioclase. Indeed, the modal amount of calcite is to some extent inversely proportional to that of augite, and both augite and plagioclase may be replaced by calcite. However, since the two groups of cobbles are apparently not isochemical with regard to CaO, some lime must have additionally been introduced from the enclosing sediment to account for the elevated values in the vert samples.

The compositional data have been plotted in the popular Harker diagram in order to illustrate possible variations in the concentrations of individual elements during differentiation and/or metamorphism (fig. 13). Here, where the major oxides are plotted against increasing silica, the following compositional trends that are common to present-day andesites (Gill, 1981) become apparent. Potash shows a crude, linear, positive correlation with silica as it is an incompatible element and relatively enriched during differentiation. Another tendency is illustrated by the

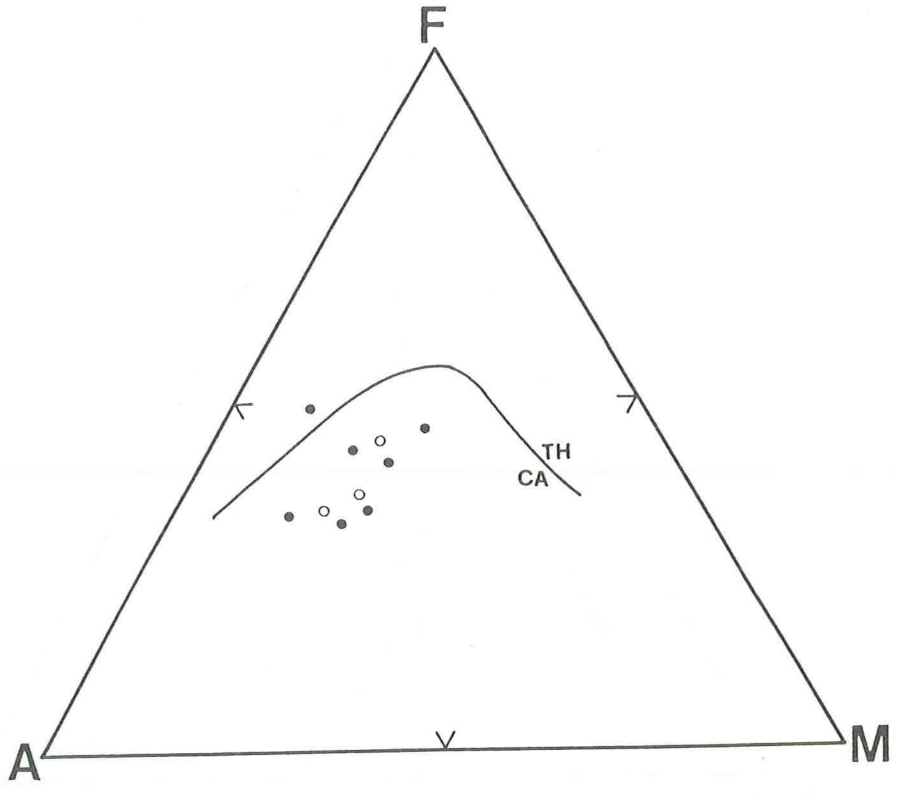


Fig. 16. Compositions of andesite cobbles (autochthonous unit) plotted in AFM diagram of Irvine and Baragar (1971). A=Na_2O+K_2O; F=FeO+0.8998 Fe_2O_3; M=MgO; all in weight percent. Same symbols as in figure 13.

highly variable CaO values which fall linearly as SiO_2 rises. Na_2O shows less variation but rises slightly with increasing silica. This may be inconclusive, however, because the lower values of Na_2O in the samples taken from the mottled facies contradict what one would normally expect from the more extensive spilitization of these samples. Furthermore, it is not known to what extent the variance in silica is due to differentiation or mobility during metamorphism.

Despite pervasive readjustments in the mineralogy of the cobbles, they can still be classified chemically as andesites using the criteria by Irvine and Baragar (1971), such as the normative plagioclase composition versus the normative color index diagram (fig. 14). "Basaltic" has often been used as a qualifier to denote the defficiency in silica and overly calcic composition of the original plagioclase in these rocks (e.g. Sawatzki, 1975). In the Ol'- Ne'- Q' projection, the andesites plot in the subalkaline field (fig. 15), which is consistent with the calc-alkaline nature of the andesites (fig. 16). In the alkalies-silica diagram (not shown here), albitization, coupled with excess K_2O, results in the apparent alkaline trend of the samples, which is typical for spilitized rocks.

3.2.3. Ophiolite Fragments

The Champsaur and St.-Didier Sandstones contain subordinate fragments derived from erosion of ophiolite members, mostly diabase fragments originating from the destruction of pillow lavas. Their share increases to substantial proportions in the St. Didier Sandstone where they were first described by Vuagnat (1947a). It is generally thought that they were eroded from Penninic units which are known to contain ophiolite remnants (Graciasky et al., 1971), notably the higher units such as the Gets and Simme Nappes in the Prealps (Vuagnat, 1943; Bertrand, 1970; Sawatzki, 1975). Though the Embrunais-Ubaye Nappes directly overlying the Champsaur Sandstone are known to contain ophiolites (Kerckhove, 1969), these occurrences are regarded as volumetrically insignificant. As discussed in section 5.2., the contribution from this source is inferred to have been minimal or lacking.

Throughout this Ph.D. dissertation, **"diabase"** refers to altered basaltic rocks derived from the destruction of pillow lavas, not altered microgabbros or dolerites. Even though the term, in this usage, has since become obsolete, the author has not abandoned it in order to comply with earlier literature relating to Taveyanne- and Val d'Illiez-similar rocks, where it is widely and firmly entrenched. As regards the mineral contents, the **diabase** fragments are quite uniform in composition. Most specimens contain albite and chlorite in various proportions, together with scattered sphene and opaques. By contrast, they display a wide range of distinctive textures reflecting the diversity of concentric internal structures in the original pillow lavas from which they were derived. Based mainly on the disposition of the feldspar, the following textures have been identified, whereby gradations between the three endmembers occur: (i) arborescent, in which the feldspar is arranged in a branching, radial, or fan-shaped pattern; (ii) spherulitic and variolitic, in which acicular or fibrous crystals are disposed in radial, rounded aggregates; and (iii) intersertal, that is, irregular plagioclase laths with wedge-shaped, chloritic interstices.

Unfortunately, it was not possible to collect sufficient **diabase** cobbles to determine their trace-element concentrations and -ratios in order to descriminate between magma series and geotectonic settings. Though such fragments may comprise 25% of the St. Didier Sandstone, the grain-size in these deposits is commonly insufficiently large to permit whole-rock sampling. In the Champsaur, where the diabase fragments usually constitute less than 1% of the rock, only one diabase cobble was found in the conglomeritic horizon of Méollion Valley, at the same location described above. Its mineral assemblage, which is uncharacteristic for the Champsaur, was recognized as being similar to certain ophiolite members of the Gets Nappe upon cursory examination by J. Bertrand (sample 216): albite, chlorite, hornblende, actinolite, clinopyroxene, epidote, calcite, sphene, and opaques. It was chemically analyzed for its major element concentrations: SiO_2 46.15; TiO_2 1.74; Al_2O_3 17.31; Fe_2O_3 3.74; FeO 6.99; MnO 0.20; MgO 6.91; CaO 7.54; Na_2O 3.09; K_2O 1.54; P_2O_5 0.31; H_2O+ 3.81; CO_2 0.50; sum 99.83.

Other material attributable to ophiolite debris includes scarce fragments of **radiolarian chert**, probably **serpentinite**, and **chloritite** comprising conversion of unstable glass to predominantly chlorite and minor opaques. Due to the general deficiency of ophiolite fragments in most of the examined samples, rare fragments of **gabbro**, **ophicalcite**, and **prasinite** might have been overlooked; they are known to occur in the Clumanc Sandstone of the Western Alps (de Graciansky et al., 1971) and the Taveyanne and Val d'Illiez Sandstones of the French Alps of Savoie (Sawatzki, 1975).

3.2.4. Acid Volcanics

The Champsaur and St.-Didier Sandstones may accommodate up to 11% of volcanic and subvolcanic rocks containing essential quartz. The mineral contents and wide range in texture are similar to the acid rocks that were independently sampled in the St. Antonin Syncline and at the village of Annot.

In the **rhyolites**, the dominant phenocryst is quartz displaying various degrees of magmatic corrosion, with additional plagioclase, alkali feldspar and, less commonly, chloritized biotite. With increasing plagioclase, the rocks may become **dacitic**. The texture of the matrix is most commonly equigranular and felsitic. When the grain-size is coarser, radial masses of quartz-feldspar intergrowths may penetrate the entire groundmass, and these rocks have been called **"globular porphyries"** (Vuagnat, 1952; Sawatzki, 1975). Such rock types would preferably be termed **spherulitic rhyolites** by English speaking petrologists. With increasing grain-size, the rhyolitic rocks grade into **microgranites** and **granophyres**. The latter are characterized by hieroglyphic intergrowths of quartz and feldspar, that is, micrographic texture.

3.2.5. Plutonic Rock Types

Apart from major volcanics, the bulk of the remaining rock material was eroded from a crystalline basement, mostly from granitic rocks. Even though the greater part of such crystalline rock fragments are granitic, only roughly have of these are, strictly speaking, plutonic rocks. Many of the acid plutonic rocks have, at one point in their history, presumably been subjected to mechanical deformation, with fracturing and minor annealing, resulting in characteristic features, such as the formation of irregular, lobate grain boundaries and various degrees of foliation. This is the justification for treating many granitic rocks separately as dynamically metamorphosed rocks, though differences may be quite subtle and distinctions somewhat arbitrary. Excluding these mylonitic and gneissose varieties, plutonic rock fragments may comprise up to 32% of the total sedimentary rock.

Ideally, the mineral assemblage of the **granite** includes quartz, sericitized albite, alkali-feldspar, in addition to mica in small amounts. The alkali-feldspar is mostly orthoclase, with some microcline, and often perthitic; the cloudy appearance of some specimens is most likely due to koalinization. Both biotite and muscovite may be present, either alone or in combination. The biotite is often partially or wholly converted to chlorite, with scattered grains of opaques and sphene. Small crystals of zircon, apatite, and sphene may be accessory constituents, with prominent epidote, either in fairly large, irregular, lumpy aggregates or trains of minute crystals. According to Sawatzki (1975), additional stilpnomelane, blue amphibole, and garnet may occur on rare occasions. In this study, solely the latter was encountered, but only as single, isolated crystal grains in the matrix of the sedimentary rock.

Apart from significant changes brought about by dynamic metamorphism, there may be substantial textural variations, as well as differences regarding grain size. This is partly the expression of the heterogeneity of the granitic body, in which tiny, sand-sized particles merely reflect different portions of the same parent rock (Vuagnat, 1952). Therefore, in a given thin section, the characteristic mineral assemblage may be quite restricted, depending perhaps simply on the position within the original rock. Where some or all the alkali-feldspar is suppressed, some fragments grade into **granodiorites**. Other particles consisting exclusively of quartz are distinguished as **"igneous" quartzites**, which presumably represent small quartzitic domains of a *granitic* rock; these may gradually pass into *"metamorphic" quartzites* when the original grains have been strongly foliated and distorted. Many granitic fragments are deficient in mafic minerals, and, as such, should be classified as **leucogranites**, particularly where the micas are excluded altogether. Again, with decreasing grain-size, the granitic fragments may progressively give way to **microgranites**. The **granite-aplites** are characterized by fine-grained, granular, micrographic textures.

3.2.6. Metamorphic Rock Types

The vast majority of metamorphic rock fragments is made up of **metamorphic quartzites, granitic gneisses,** and **mica-schists.** As mentioned above, the greater part of such fragments is inferred to have developed from predominantly mechanical forces acting on an initially granitic rock at high structural levels, perhaps along planar surfaces of minor displacement within the same plutonic rock body described above. The transformations are limited to various degrees of fracturing, incipient recrystallization or annealing, sutured grain boundaries, foliation, strain shadows in quartz, and the like; otherwise there are more similarities than differences with most of the granitic rock types mentioned in the heading above, particularly with respect to mineral assemblages.

The total amount of metamorphic rock types averages 11% on the whole, and may approach 28% in the more internal, parautochthonous units. This is in marked contrast to the quantity determined in the structural units along the transverse of the Alps of Savoie, which never comprises more than 1% of the rock (Sawatzki, 1975). Some - but presumably not all - of the apparent variation is perhaps related to operator error, i.e. effects arising from possible inconsistencies in interpretation or classification with Sawatzki (1975), who probably excluded many of the dynamically metamorphosed rock types from this category.

The association of minerals in the **granitic gneiss** is essentially that of a granite: quartz, feldspar, muscovite and/or biotite, with extensive sericitization and chloritization. In the **mica-schist**, however, there is considerably more muscovite and less feldspar than in the typical granite; the finer-grained, **phyllonitic** varieties contain anastomosing networks of muscovite and sericite along schistosity surfaces. The essentially monomineralic **quartzites** are characterized by irregular grain boundaries, with or without preferred orientation of its constituents, and often, as in any metamorphic rock type, triple junctions in which solid-state annealing has attained equilibrium, producing grain boundaries that intersect at 120°. **Epidosites** are composed mainly of epidote and quartz, frequently with chlorite, sphene, and opaques. However, in that the normal granite may contain epidote, this rock type remains elusive. Some of these masses might represent such deuteric alterations - and should thus not be regarded as a metamorphic rock - whereas others may be truely metamorphic, especially where epidote comprises over 70% of the rock. Even though **diabase** and **serpentinite** are actually metamorphic, they have more appropriately been treated as ophiolitic rocks.

3.2.7. Sedimentary Lithoclasts

A striking characteristic of the Champsaur Sandstone is its consistent deficiency in sedimentary fragments, even in the more internal, parautochthonous sandstone units where the dilution by andesite clasts is nonexistent. This is another major compositional disparity with the rocks associated with the Taveyanne Sandstone. In the Champsaur, the amount of sedimentary fragments averages approximately 1.1% and never exceeds 3.6%, rising to a modest average of about 15% in the St. Didier Sandstone. In the transverse of the Savoie Alps, by contrast, the amount may easily rise close to 50% in both the Ultrahelvetic and Val d'Illiez Sandstones, with a low of 15% in the Taveyanne Sandstone, the variance being largely governed by massive addition or removal of volcanic rock material, mostly andesites (Sawatzki, 1975). Unfortunately, the petrographic study of sedimentary fragments was greatly hampered by the scarcity of such fragments in the rock. Therefore, the petrographic description which follows might not be complete or truly representative of the rocks. However, it is believed that most have local origins, either from the underlying sediments or from parautochthonous Mesozoic and Priabonian thrusts; otherwise, it is imaginable that more internal Penninic or even Austroalpine units supplied additional amounts (Vuagnat, 1952).

The Champsaur Sandstone contains sedimentary rock fragments composed largely of clastic particles, notably arenaceous rocks. In most of these, quartz and carbonate fragments are prominent constituents. According to the proportions of these fragments, the greater part of the arenaceous rock types can be classified as **quartz arenite, sublitharenite,** and **lithic arenite** with decreasing quartz. Other fragments discernible in thin section are feldpar, muscovite, glauconite, zircon, apatite and opaques. **Glauconitic sandstones** are distinguished by their abundance in rounded glauconite pellets associated with siliclastic and carbonate grains; these have been assigned to the Albian (Sawatzki, 1975), presumably the **Helvetic Gault.** The **micaceous marls** can most likely be attributed to shale partings of the Champsaur Sandstone, reworked from the strata directly below (Vuagnat, 1952; Sawatzki, 1975).

Numerous calcareous rocks were found, mostly micrites with varying proportions of siliclastic and biogenic fragments. Depending on the nature of this material, the calcareous fragments can be grouped as pure **micrites, sandy micrites,** and **biomicrites.** The latter are **foraminiferal** and often **nummulitic,** and are related to reworkings of the underlying Priabonian **Schistes à Globigérines** and **Calcaires Nummulitques** Formations. Other calcareous fragments include **oolitic limestones** and equigranular, **dolomitic sparites.**

Infrequently, the Champsaur and St. Didier Sandstones embody **radiolarian chert**, sometimes with partial preservation of the original organic textures. They are charged with finely crystallized haematite which imparts a red, dusty appearance in transmitted light (Vuagnat, 1952). The red pigmentation suggests they were not dreived from those occurring in the Klippe de Soleil Boeuf, which are green, due to the presence of chlorite.

4. PETROGRAPHIC VARIABILITY

4.1. Introduction

Whereas the preceding section was mainly concerned with the qualitative petrographic description of the individual clasts that make up the Champsaur and St. Didier Sandstones, emphasis in this section is on the variability of these components within and amoung various sandstone units. It is essentially a quantitative treatment of the petrographic and mineralogical composition of the sandstones, as determined largely by point counting.

Detailed quantitative analyses have grown out of the need to devise a lithostratigraphic basis for long-distance correlations in flysch successions that appear to be compositionally uniform along much of the alpine arc. Whereas Vuagnat (1952) mainly dealt with the compositional characterization of individual units and their variation through geologic time, Martini (1968) and Sawatzki (1975) additionally determined the controls exerted by grain size on some components. In this study, petrographic composition is also determined as a function of both the stratigraphic level and paleocurrent direction *within* a turbidite succession. A quantitative analysis of roundness is also included in order to get a notion of the distance travelled from the source. Thus one textural and four compositional parameters were determined, mostly for 9 different components:

1) compositional characterization and comparison of individual sandstone units and subunits (table IV);
2) compositional variation with increasing age from one major unit to the other in the direction of thrusting (fig. 17 and 18);
3) vertical compositional variation within the flysch succession of the autochthonous unit (fig. 19);
4) compositional variation in relation to paleocurrent directions of autochthonous unit (fig. 20); and
5) effects of composition and grain size on roundness, regardless of structural unit (fig. 21).

4.2. Analytical Methods

4.2.1. Sampling Procedure

A total of 61 sandstone samples were analyzed by conventional point counting in thin section. The sampling was spread out over the various units and subunits of the Champsaur, and periodocally along the route nationale N 537, south of the village of St. Didier.

In the autochthonous unit of the Champsaur, whenever it was possible to measure a paleocurrent direction during detailed sedimentological recording of the 12 measured stratigraphic sections (see section 2.3.), one sandstone sample was taken from the same turbidite bed and analyzed for its composition by point counting in thin section. Therefore, for 28 of the 33 samples taken from the autochthonous unit, the exact stratigraphic level and paleocurrent direction of the turbidite bed is known in addition to its petrographic and mineralogical composition.

4.2.2. Grain Size

When interpreting the petrographic characteristics of sandstones, grain size must be taken into consideration; it is widely known that it may have a profound influence on composition. Several studies in the Taveyanne Sandstone have shown that it affects several components, whereby the rise in the relative abundance of andesite with increasing grain size is the most significant observation (de Quervain, 1928: Martini, 1968; Sawatzki, 1975). Therefore, grain size must be precisely defined and maintained during sampling in order for the results to be internally consistent.

In this study, samples were carefully taken from that portion of the graded turbidite bed where the average diameter of the largest particles was as close as possible to 2 mm; individual pebbles suspended in a uniformly finer-grained matrix were disregarded. The diameter of 2 mm was chosen after initial observations in the field revealed that it comprises the coarsest possible size grade available in most turbidite beds. This was necessary in order to attain the highest possible percentage of genetically distinctive rock fragments. Later, it was found that this was not always possible in the St. Didier Sandstone, so most of the samples taken from this area are actually finer-grained.

It is often not clear which grain size was used for this purpose by previous authors working in the Taveyanne Sandstone (Vuagnat, 1952; Sawatzki, 1975; Lateltin and Müller, 1987). Given the generally fine-grained nature of these deposits, it might very well have been smaller, possibly in the range of 1 mm (Vuagnat, pers. comm.).

4.2.3. Point Counting

The frequencies of individual constituents were measured using the automatic mechanical stage and counting device manufactured by Swift and Son, London. The regular spacing of counts and transverses was such that the number of counts approximately equalled 1200 per thin-section. This brings the total number of counts in this study to about 73.000.

4.2.4. Definition of Components

Relative abundances have been obtained by point cointing for 9 basic components. The interstitial matrix and cement were ignored, and the sum of the components recalculated to 100%. Additional parameters were derived by direct addition (And + Plag) or division (Plag/Quartz) of two of these measures. Unless stated otherwise, the data concerning **andesite, acid volcanics, sedimentary, plutonic,** and **metamorphic** clasts refer directly to the sum of the components discussed previously under the corresponding headings in the section treating the petrographic description of the constituents. All of these values are in reference to *rock* fragments, and not the mineral debris derived therefrom.

Whereas **ophiolite** was used in a previous heading, **diabase** (referring to fragments of altered submarine pillow basalt, not altered microgabbros or dolerites) is used here for the sum of these components because it constitutes the greater part of the ophiolitic material. Though **radiolarian chert** was also mentioned in conjunction with ophiolites, it is treated solely as a sedimentary particle here.

Sawatski (1975) employs the confusing terms **"éléments andésitiques"** and **"éléments volcaniques"** without specifically stating whether it is meant to include the associated mineral debris. After an inspection of his thin-section collection, there was reason to believe that this might be the case. This was subsequently confirmed by G. Sawatzki in response to a written inquiry. Despite no apparent difference in the abundance of andesitic debris, his values are substantially higher than those determined here. Though both Vuagnat (1952) and Martini (1968) specify that their **"éléments volcaniques"** values include isolated minerals, diabase fragments were also taken into account, which does not conform with the analytical procedure employed here. Again, to avoid ambiguity in this study,

andesite refers to the relative amount of andesitic *rock* fragments, not the mineral debris. Given the relative insignificance of mafic minerals and diabase to total plagioclase, the éléments andésitiques and éléments volcaniques values of any of these authors are closer to the **And + Plag** arrived at here.

Both **Plag** and **Quartz** are treated as mineral debris, regardless of source. The same holds for **Other**, which represents the entire mass of mineral matter other than plagioclase and quartz.

Recall that the vast majority of granitic rock fragments was partitioned into **plutonic** or **metamorphic** rock fragments on the basis of dynamic metamorphism.

4.3. Characterization and Comparison of Sandstone Units

As a result of the complex evolving nature of the migrating fold- and thrust belt, the range of compositional variation is wide in the St. Didier and Champsaur Sandstones, and extremely rapid in view of the short distance travelled in the direction of thrusting. This is most pronounced in the Champsaur, where several, compositionally contrasted units are traversed over a distance of only 5 km, or even considerably less where they pinch out near Méollion. While compositional variation is abrupt when major thrust planes are crossed, there is relatively little internal variation within a given sandstone unit, which stems from the characteristic time lag between deposition and subsequent underthrusting of the units.

In figure 3, the three major sandstone units have been sequentially numbered (1 to 3) according to age, becoming progressively younger from SE to NW. These, in turn, have been subdivided into subunits (a, b, or c) which are inferred to have suffered little displacement relative to the major unit (a). The respective compositions of all these units and subunits are shown in table IV. With these divisions it is not meant to introduce an additional classification scheme; they are merely *structural*, intended to aid in the estimation of compositions in the field. The terms "Grès de Taveyannaz I, IIa, IIb, III, and IV" were introduced by Vuagnat (1952) with the intention of providing a classification scheme on the basis of *composition*, like the descriptive terms "rich", "typique", and "pauvre" employed by Martini (1968), and "intermédiaire" by Sawatzki (1975).

4.3.1. Unit I

Structurally, sandstone unit 1 belongs to the highest and most internal of the parautochthonous units. It grades upwards into the olistostrome that lies at the base of the Embrunais-Ubaye nappes. With regard to its (1) highest and (2) originally most internal structural position, (3) relationship with overlying olistostrome, and (4) overall petrographic and mineralogical composition, it is virtually identical to the **Ultrahelvetic Sandstone** of the Savoie Alps (see Martini, 1968, and Sawatzki, 1975), the **Annot Sandstone** of the southern French Alps (Apps and Ghibaudo, 1985), and probably the **Flysch des Aiguilles d'Arves** (see Barbier, 1956; and Deharveng et al., 1987) into which it passes towards the N.

Table IV. Modal compositions of graywackes. Unit numbers refer to sandstone members designated in figure 3.

fragment	Unit 1 (4 samples)			Unit 2a (8 samples)			Unit 2b (3 samples)			Unit 2c (2 samples)		
	min - max	mean	st.d.	min - max	mean	st.d.	min - max	mean	st.d.	min - max	mean	st.d.
diabase	0.1 - 0.3	0.2	0.1	0.1 - 2.2	0.6	0.8	0.0 - 0.1	0.0	0.1	0.2 - 0.5	0.4	0.2
plutonic	12.7 - 27.2	21.5	6.3	12.3 - 32.4	23.9	6.5	10.1 - 15.8	12.8	2.9	15.6 - 20.2	17.9	3.3
sedimentary	0.4 - 1.2	0.8	0.4	0.0 - 1.2	0.5	0.5	0.0 - 0.6	0.3	0.3	0.7 - 2.0	1.4	0.9
metamorphic	15.0 - 22.6	19.0	3.2	4.6 - 28.2	15.7	8.7	7.1 - 10.0	9.0	1.6	15.7 - 19.1	17.4	2.4
andesitic	---- - ----	----	----	0.0 - 29.1	8.5	11.8	10.1 - 19.2	14.0	4.7	0.0 - 0.2	0.1	0.1
quartz	29.3 - 44.5	36.4	6.2	18.7 - 40.3	27.0	7.3	31.5 - 37.8	33.7	3.6	35.4 - 42.5	39.0	5.0
plagioclase	4.8 - 6.3	5.6	0.7	3.1 - 17.8	9.3	5.9	13.7 - 18.1	16.1	2.2	8.5 - 9.3	8.9	0.6
acid volc.	2.0 - 3.3	2.6	0.5	0.8 - 4.9	2.5	1.5	0.9 - 3.0	1.8	1.1	3.4 - 6.5	5.0	2.2
other	12.0 - 15.3	14.0	1.5	8.6 - 14.8	12.1	1.9	11.7 - 13.0	12.4	0.7	9.9 - 10.4	10.2	0.4

fragment	Unit 2d (1 sample)	Unit 3a (33 samples)			Unit 3b (2 samples)			Unit 3c (1 sample)	St. Didier (7 samples)		
		min - max	mean	st.d.	min - max	mean	st.d.		min - max	mean	st.d.
diabase	----	0.0 - 2.9	0.4	0.7	0.4 - 1.1	0.9	0.5	----	5.6 - 25.3	16.1	4.4
plutonic	15.1	4.5 - 23.8	9.5	4.0	6.1 - 12.4	9.3	4.5	8.6	5.0 - 17.5	11.5	4.7
sedimentary	2.2	0.0 - 3.6	2.1	1.1	1.4 - 2.2	1.8	0.6	0.6	6.0 - 23.5	15.8	7.3
metamorphic	6.9	1.9 - 21.8	7.1	4.1	1.4 - 3.4	2.4	1.4	4.9	5.8 - 13.7	8.2	3.3
andesitic	10.4	0.6 - 62.0	35.1	16.1	30.6 - 31.5	31.1	0.6	37.7	---- - ----	----	----
quartz	42.6	10.9 - 41.0	19.4	17.4	23.3 - 25.0	24.2	1.2	25.3	22.1 - 34.0	27.3	4.7
plagioclase	11.0	1.9 - 27.5	15.2	5.3	15.2 - 22.1	18.7	4.9	14.2	1.7 - 4.5	2.8	1.0
acid volc.	4.3	0.3 - 11.6	3.1	2.5	0.5 - 1.1	0.8	0.4	1.2	1.0 - 4.9	2.8	1.7
other	7.6	3.5 - 16.4	8.5	3.4	8.8 - 13.5	11.2	3.3	7.4	6.9 - 26.0	14.6	7.0

The most distinctive feature that is common to these units is the lack of andesite and diabase detritus along the greater part of the alpine arc. In the Champsaur, however, there are subtle petrographic differences to analogous units. Firstly, whereas in the lateral equivalents there is commonly a *total* lack of diabase fragments (Vuagnat, pers. comm.), in unit 1 they may appear in trace amounts, never exceeding 0.3% of the total rock. Though all the samples that were analyzed by point counting happened to contain a few diabase grains, it may be necessary to cut several thin sections from a single hand specimen before such a particle is encountered. Secondly, as opposed to the **Ultrahelvetic Sandstone** (see Sawatzki, 1975), the samples from unit 1 are significantly deficient in sedimentary components, which are compensated mostly by fragments derived from a crystalline basement source.

In the field, the sandstones belonging to unit 1 are easily recognized by their light-gray appearance which is in contrast to the increasingly dark-colored, greenish and brownish nature of the more external units, especially in the weathered state.

4.3.2. Unit II

The second unit is essentially distinguished from unit 1 by the moderate introduction of andesite fragments and associated increase in frequency of plagioclase grains. This is a clear indication that, in the volcaniclastic rocks, plagioclase should be allocated primarily to andesite. Using the sum of plagioclase and andesite as a lithostratigraphic marker, the samples from unit 2 most closely resemble Sawatzki's (1975) **Grès de Tavayanne intermédiaires** which, similarly, evolve from the Ultrahelvetic Sandstone.

There is however a wide range in andesite contents between individual subunits which may contain between 0.1% and 14% on average; individual turbidite beds are capable of accommodating up to 20-30%. This variance is in all likelihood more attributable to the difficulty in correctly interpreting the intricate structural position and history of the subunits than it is to the lateral or vertical variation within a given unit, which was never unequivocally discerned in the field. Some of this variation is perhaps due to minor displacements of individual subunits relative to one another, causing compositional jumps.

A case in point concerns the apparent marked lateral compositional variation of **unit 2a** between its segment in the SW and that in the NE. Whereas in the vicinity of the Drac Blanc the sandstones are compositionally more typical of the intermediate type, SE of the Palastre they closely resemble those of the autochthonous unit (3a) in that they may contain up to 29% andesitic fragments. In view of the common structural contact with the underlying autochthonous unit, the compositionally contrasted segments were both assigned to the same thrust sheet even though there is no apparent lateral transition between them in the field on account of the extensive masses of rock waste and Quaternary cover in the crucial area.

Unit 2b may safely be assigned to the structural framework of the second unit, in particular the adjacent unit (2a) which is compositionally similar. Together they comprise a thrust sheet that is fault-bounded on its lower and upper surfaces, both of which may be connected with those that delimit unit 2c.

Unit 2c serves as another problematic example. When viewed from the north it is readily perceived as a separate stratigraphic or structural entity, and the bodies of strata are separated by a discrete planar surface. Due to the conformable contact it is tempting to interpret the abrupt compositional change as sedimentary. This however appears improbable since no abrupt vertical variations were found during a detailed petrographic investigation of the autochthonous unit (see section 4.5.); nor were they ever detected in other units. It is more likely that the sharp contact represents a low-angle thrust, though the outcrop conditions are such that this cannot be confirmed with certainty in the field. The strata have been assigned to unit 2 because (1) they directly overly the autochthonous unit, and (2) they are conspicuously deficient in andesite detritus, whereby the amounts are more comparable to those determined in unit 2 than to those determined in unit 3.

Because its relationships to the surrounding rocks have been largely eroded, the interpretation of **unit 2d** poses a more difficult problem. Forming the summit of the Prouveyrat, it succeeds units 2 and 3 upwards. Since it is the highest structural unit, associating it with unit 1 would at first thought provide a plausible solution. This would require that the inserted stack of Mesozoic nappes underlying unit 1 pinches largely out towards the NW. On the other hand, unit 2d could conceivably represent a tectonic sliver that was detached from unit 2a and tectonically entrained. Due to its close petrographic resemblance to unit 2a, this interpretation is favored here.

4.3.3. Unit III

Unit 3 comprises the youngest and most external of the flysch units in the Champsaur. It is characterized by its uniformly high contents of andesite clasts and associated plagioclase grains, both of which are at the highest attainable proportion. Consequently, the rocks are the most susceptible to reactions involving these unstable constituents, giving rise to intermittent but widespread laumontitization. The characteristic mottling thus imparted is the most prominent expression of incipient metamorphism in these rocks. A comprehensive treatment of the secondary mineral assemblages will be given in chapter 6.

In terms of original petrographic composition and secondary mineral associations produced in these rocks, they are comparable to the Taveyanne Sandstone described by Martini (1968). More specifically, with regard to overall petrographic composition, they are akin to the **Grès de Taveyanne typiques** which are defined by similar And+Plag and Plag/Quartz values (see Sawatzki, 1975). When compared in detail with these, the Champsaur samples are characterized by less amounts of sedimentary fragments, and somewhat more acid volcanics, quartz, and diabase which is missing altogether in the **Grès de Taveyanne typiques** (see Sawatzki, 1975). The **St. Antonin Syncline** is apparently also devoid of the greater part of ophiolite fragments, with the exception of gabbro (Boucarut and Bodelle, 1969).

When, on the other hand, the composition of unit 3 is measured against that of the more internal units of the Champsaur, the most apparent dissimilarity is the exceptionally high proportion of andesite and plagioclase debris. This is accompanied by an equal reduction in associated quartz, plutonic, metamorphic, and "other" fragments, all of which are mostly linked to a crystalline basement source. This arises from the "constant sum effect": since the sum of the components invariably equals 100%, a massive addition of one component may effectively suppress the relative amounts of other components, so the reduction of a given component may not necessarily be inferential. For instance, this may be understood as the arrival of an andesitic thrust sheet, or erection of andesitic volcanoes near the basin margin, rather than levelling down of a predominantly crystalline source area.

Unit 3a is areally the most extensive of all the units and subunits of the Champsaur. Conjointly with the underlying Schistes à Globigérines and Calcaires à Nummulites Formations, it is entirely autochthonous and transgressive onto the Pelvoux Massif in the north and its Mesozoic sedimentary cover in the south. It was the subject of the detailed sedimentological study outlined in section 2.3. A comprehensive analysis of petrographic variability as a function of stratigraphic level and paleocurrent direction within this unit is deferred until sections 4.5. and 4.6., respectively.

In subunits **3b** and **3c**, there are virtually no petrographic deviations from unit 3a. This is an indication that they are barely dislodged from the autochthonous unit and not far displaced from their original site of deposition.

4.3.4 The St. Didier Sandstone

After an extensive erosional gap, the Champsaur Sandstone reappears farther to the west as the St. Didier Sandstone in Devoluy (fig. 1). Erosion of intermediate sandstone members results in the apparent radical change of characteristics, which actually is inferred to have been essentially gradual. Apart from a substantial decrease in grain size and marked change in sedimentary facies, there are several petrographic variations. Whereas, in the preceding unit of the Champsaur, andesites are the predominant constituent, they are entirely missing in the St. Didier Sandstones; nor is there any detritus of related ferromagnesian

minerals. The exclusion of andesites also gives rise to the reduction in the number of associated plagioclase grains. It is mainly compensated by a substantial rise in diabase, sedimentary, quartz, glauconite, and "other" values, and to a lesser extent plutonic and metamorphic rock fragments. This demonstrates once more the impact of the constant sum effect: the increase in some, if not most, of the components is governed largely by the removal of andesites.

With regard to structural framework and overall composition, the St. Didier Sandstone conforms with the **Val d'Illiez Sandstone** of the Swiss Alps (Vuagnat, 1947a). When the quantity of diabase fragments in the St. Didier Sandstone is weighed against that in the Val d'Illiez Sandstone of the Savoie Alps (Sawatzki, 1975), there is a greater amount in the former (16% versus 4% on average). Furthermore, while andesite fragments are entirely missing in the St. Didier Sandstone, such fragments nevertheless comprise 12% of the Val d'Illiez Sandstone (see Sawatzki, 1975); the latter also contains considerably more sedimentary rock fragments which may constitute nearly half of the total rock (see Sawatzki, 1975).

The **Clumanc Sandstone** is more comparable to the Val d'Illiez Sandstone in that it may contain andesite and ophiolite fragments in similar amounts (see Bodelle, 1971, pp. 257 ff.). It differs from both the St. Didier and Val d'Illiez Sandstones by the exceptionally high percentage of sedimentary cobbles (mostly Upper Cretaceous limestones) which may locally comprise up to 95% of the rock (see Bodelle, 1971).

4.4. Compositional Variation Through Geologic Time

In the preceding section, the compositions of 9 different units and subunits were briefly characterized. Although they appear to be compositionally distinct and contrasted, it is apparent that they are in many ways strikingly similar to other units distributed elsewhere along the alpine arc. This stems from a series of evolutionary stages which is apparently common to many turbidite successions of the fold- and thrust belt. The remarkable regularity demonstrates the value in devising a quantitative basis for petrographic comparisons. It is hoped that, one day, petrographic composition may be confidently used as a measure of age, original structural position, relative displacement, and long-distance correlation of individual sandstone units hundreds of kilometers apart.

A coherent picture emerges when the modal compositions of individual subunits are averaged and plotted against their relative positions prior to thrusting. This is shown in figure 17 which essentially portrays the petrographic variation through geologic time, i.e. from one major unit to the other, in the direction of thrusting. Petrographic variability is mainly governed by the amount of andesites.

They appear in unit II and increase regularly until ultimately they are removed in equal amounts. A rise in the amount of andesite entails a similar rise in plagioclase and, hence, plag/quartz. This effectively suppresses the material derived from a crystalline basement source, i.e. plutonic, metamorphic, quartz, and "other" fragments, all of which correlate negatively with andesite. While "other" fragments fully regain the amount they had prior to the appearance of andesites, the quantities of plutonic, metamorphic, quartz, and, to a lesser extent, plagioclase and plag/quartz fall short of the initial values. This is mostly due to the concurrent rise in diabase and sedimentary fragments which, like acid volcanics, are apparently *not* influenced by the constant sum effect. On the contrary, the values may rise simultaneously with those that are attributable to andesite, so the increase is presumably of major paleogeographic significance, particularly with regard to diabase and sedimentary fragments.

Figure 17 displays most of the orderly changes that were detected by Sawatzki (1975) in the Savoie Alps when he arranged his data similarly in figures 2 and 5. There, by contrast, the sandstones intermediate between the Grès de Taveyanne typiques (unit III) and the Grès de Val d'Illiez (Grès de St. Didier), that is, the Grès de Taveyanne pauvres, have not been eroded. Nevertheless, successive sandstone members display the same progressive rise and fall in the amount of andesites which similarly suppress the other coponents, though in different proportions. Differences of this sort are due to inconsistencies in the definition of components and the grain size that was used for modal analysis (see sections 4.2.2. and 4.2.4.). Given such inconsistencies, it is the variation itself that matters when attempting to correlate individual sandstones units, not the absolute amount. For this purpose, it is felt that plag/quartz is the most effective discriminant because the values determined by Sawatzki (1975) closely match those arrived at in this study. Since it is an easily defined, unambiguous *ratio*, it is perhaps less prone to deviations caused by operator error, inconsistencies in analytical methods, and the like.

Herein lie the true discernible disparities between the transverses of the Savoie Alps (Sawatzki, 1975) and the Dauphiné:

1) While in the Savoie Alps diabase fragments appear in the wake of andesite debris, in the Dauphiné they emerge before these and eventually rise to greater proportions.
2) Whereas in both transverses andesites appear in approximately equal amounts, in the Dauphiné they vanish earlier: andesites are lacking in the St. Didier Sandstone but not in the Val d'Illiez Sandstone.

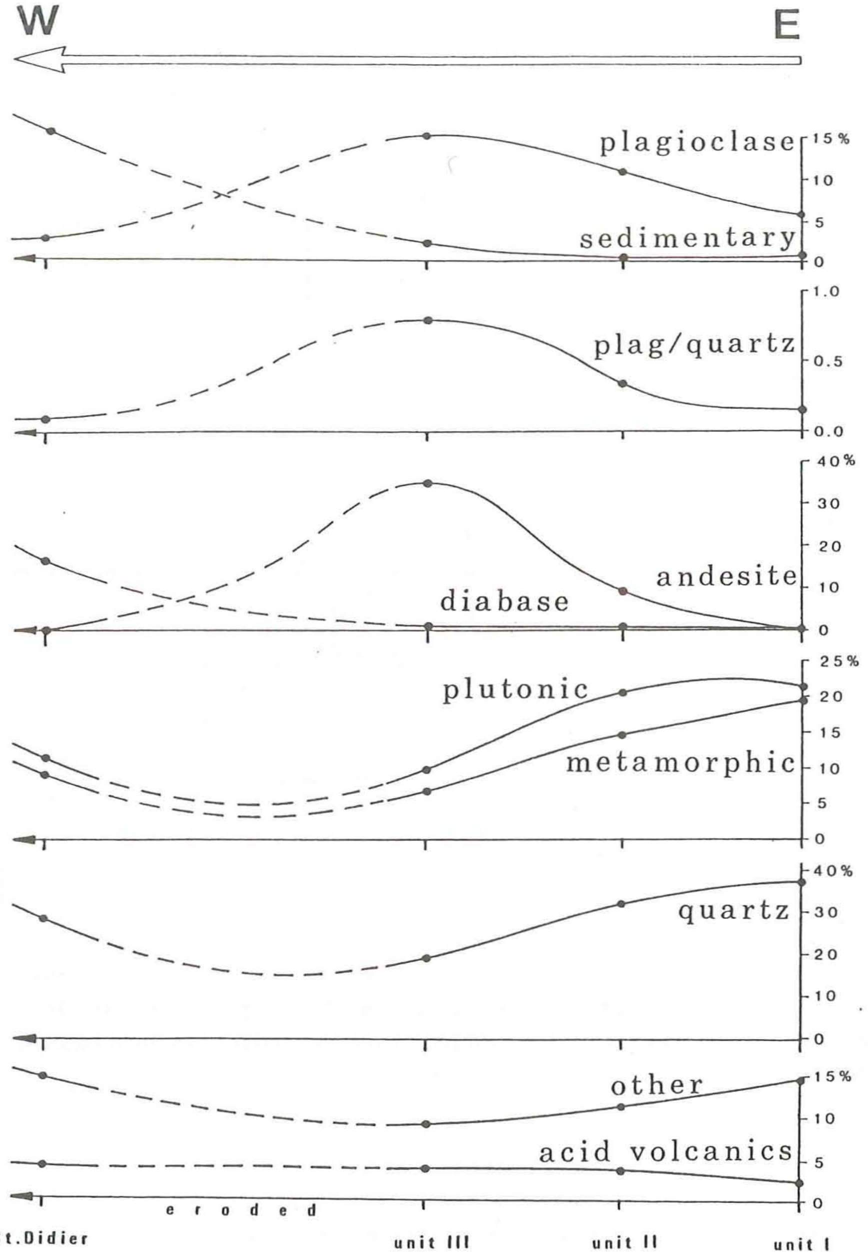


Fig. 17. Average modal compositions (see table IV) of major sandstone units plotted against their respective positions prior to thrusting, displaying lithologic variations from one major unit to the other in the direction of thrusting (cf. Sawatzki, 1975, figures 2 and 5). Spacing between unit III and St. Didier Sandstone was arbitrarily chosen to be twice that between more internal units of the Champsaur.

3) While in the Dauphiné sedimentary rock fragments increase regularly in the direction of thrusting, the invariably higher proportions in the Savoie Alps merely display the successive decrease and rise associated with the constant sum effect.
4) Whereas in the Dauphiné the quantity of acid volcanics is essentially uniform, in the Savoie Alps the initially equal value decreases progressively in the direction of thrusting.

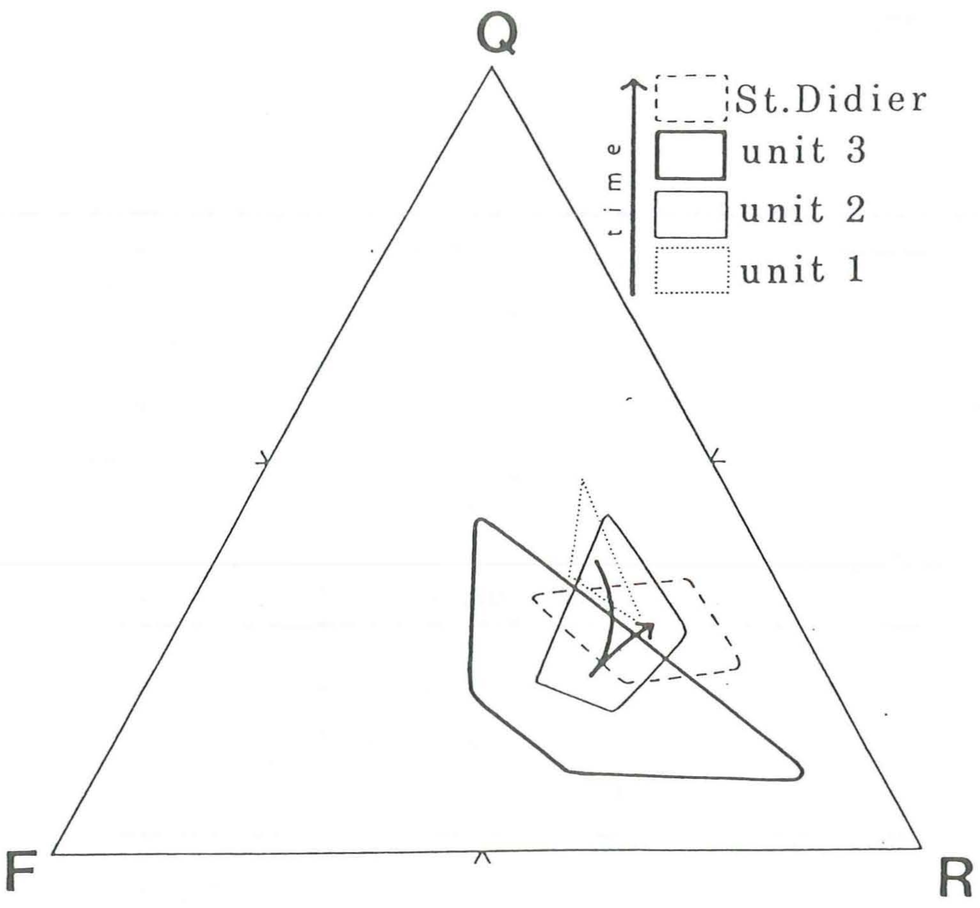


Fig. 18. Average modal compositions of major sandstone units plotted in the QFR triangle (Q=quartz; F=feldspar; R=rock fragments) displaying gross lithological variation through geologic time. Larger scatter is commonly due to larger number of individuals in a sampled population. All samples may be classified as lithic graywackes on this basis.

Nonetheless, it is clear that the massive introduction of andesites is the immediate controlling factor for petrographic variability. The results are fully consistent with the hypothesis that andesitic volcanoes were incorporated into a nappe and transported to the basin margin in the foreland, away from the Alps (Vuagnat, 1952; Sawatzki, 1975). It is conceivable that, in the course of underthrusting, the extensive Variscan basement massif that had acted as the major source from the start was partially overrun by an andesitic nappe which was subsequently removed by regional uplift and erosion. Erosion of predominantly crystalline rocks resumed, either by incision into the basement underlying the andesitic nappe or by exposure of newly formed granitic thrusts in a more external portion of the basement massif that had not been reached by the initial andesitic thrusts. Alternatively, andesitic volcanoes might have been erected directly on an external crystalline massif adjacent to and on the internal side of the basin margin, then removed by erosion or underthrusting (see section 5.3.). In any case, early on in the sequence of events in the Champsaur, diabase and sedimentary rock fragments were increasingly introduced in subordinate amounts, announcing the progressive advance and rise of more internal nappes (see Chapter 5).

Plotting the modal compositions of individual units separately in the QFR triangle exposes the major role of andesites, particularly in the beginning of the evolutionary cycle (fig. 18). The introduction of substantial amounts produces an increase in F (mostly plagioclase) and R (mostly andesitic fragments) in approximately equal proportions; this, in turn, entails an important reduction in the proportion of quartz. Erosion or removal of the andesites by underthrusting reverses this trend somewhat, but with a disproportionate reduction in F and R; the quantity of rock fragments is more or less maintained by the concurrent supply of diabase and sedimentary fragments in increasing amounts.

4.5. Vertical Compositional Variation Within Autochthonous Unit

The precise stratigraphic level is known for 28 sandstones samples which were taken from the autochthonous unit and analyzed for their petrographic composition by point counting in thin section. They were sampled at irregular intervals in the 12 recorded stratigraphic columns (see section 2.3.), whenever it was possible to measure a paleocurrent direction (see following section). Once the stratigraphic sections were correlated and aligned with respect to adjacent columns (fig. 8), the stratigraphic position of each sample was projected laterally along the horizontal into column number 11 where the deepest and oldest beds of the turbidite fill are preserved. The modal compositions were plotted as a function of their respective stratigraphic level within this reference column and subsequently joined by straight lines to construct a variation curve (fig. 19). In this manner, gradual lithological variations during deposition of nearly 650 m of sediment were recorded.

With respect to virtually all components, abrupt lithological changes take place between samples immediately overlying each other. It is believed that these rapid changes lie within the range to be expected from random spot sampling. Given the short interval and, therefore, insufficient time span between successive samples, the irregular fluctuations are apparently not associated with changes in the configuration of rock materials exposed at the source. Since the same grain size was carefully maintained throughout the sampling procedure, no matter what the thickness of the bed, it is also unlikely that sudden lithological changes are related to selective hydraulic sorting along the length of the turbidity current; individual components would be preferentially deposited according to grain size, regardless of

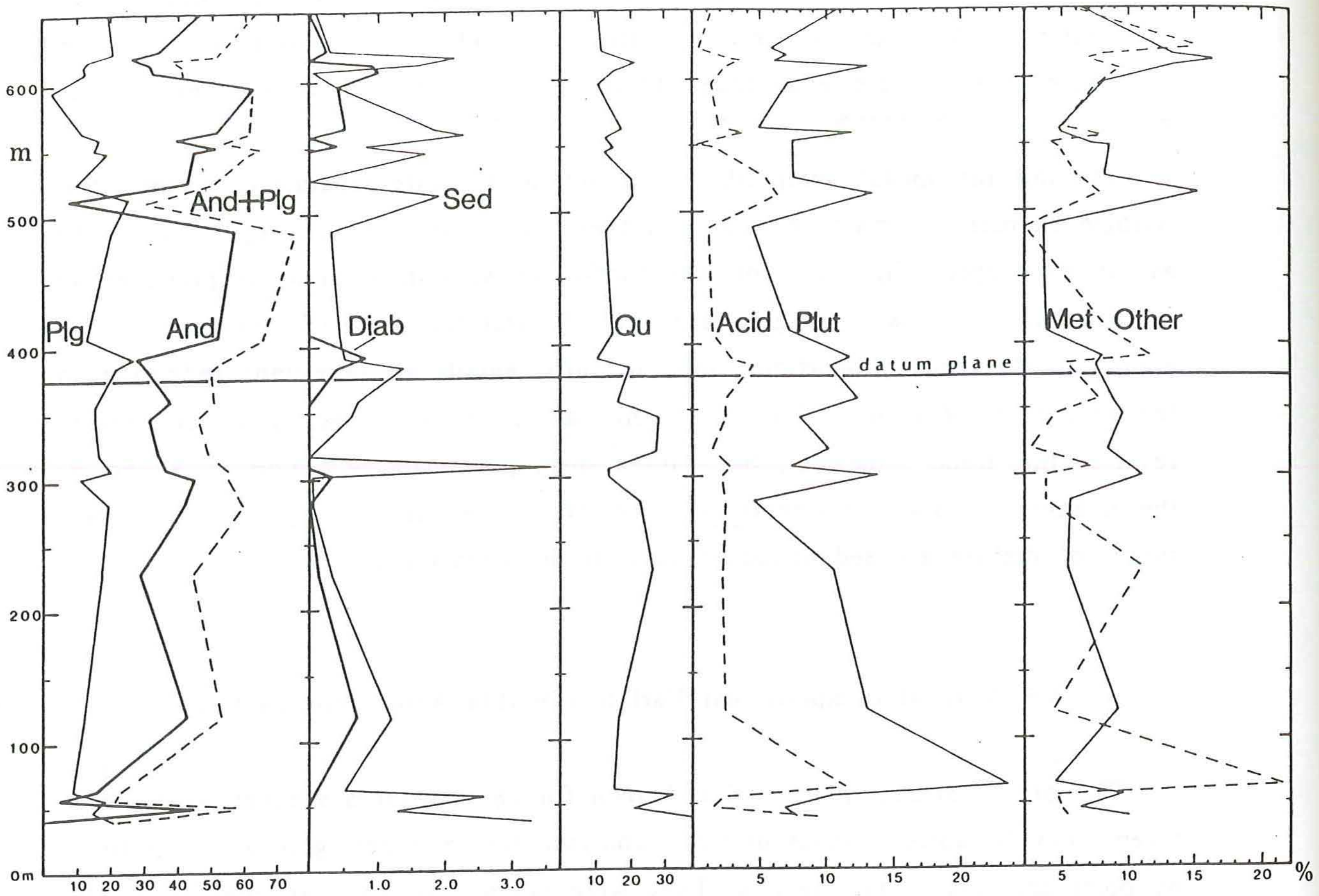


Fig. 19. Vertical petrographic variability in sandstone unit 3a. Ordinate refers to stratigraphic level of reference column number 11 (fig. 8) into which the stratigraphic position of each analyzed sample was projected along the horizontal. Datum plane corresponds to same plane of reference shown in figure 8. No data below 40 m.

the distance travelled by the flow. As outlined in the following section, the influence exerted by paleocurrent direction may be safely ignored too.

Once more, variance in some components is apparently influenced directly by that of andesite. With respect to individual samples, many of the erratic compositional peaks of andesite are countered by equally drastic changes in the amount of other constituents, for instance at 50 and 520 m above the base of the reference column. On a larger scale, when the curves are smoothed out, there is a small, progressive rise in the amount of andesite towards the top of the sedimentary sequence; this is compensated by a barely perceptible decrease in some of the other constituents, like acid volcanics, quartz, and plutonic fragments.

In that diabase and sedimentary fragments do not display any variation trends in the autochthonous unit (at this scale), andesite shows the only predictable variance of paleogeographic significance (see preceding section). Andesite averages approximately 20-30% near the base of the sequence and rises progressively towards the top where the average is more like 40 or 50%. This systematic rise could be related either to the steady advance of an andesitc nappe, or to gradual appearances of andesitic volcanoes close to the depositional basin.

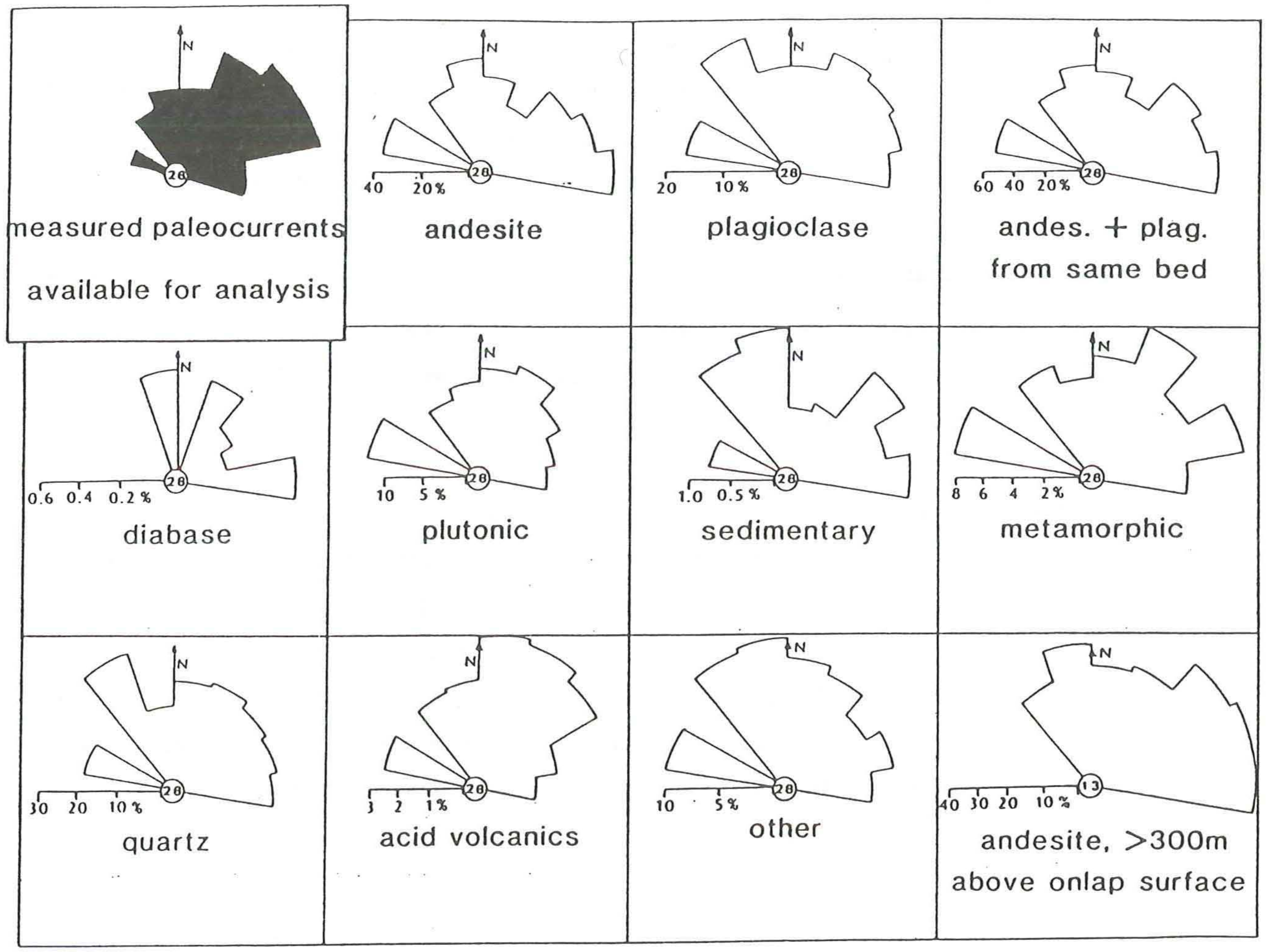


Fig. 20. Directional petrographic variability in autochthonous sandstone unit. For ten components, the relative abundances were averaged separately for each directional class and plotted on compass roses. Note that And+Plag refers to the sum of the relative abundances determined in one and the same thin section, not the entire sum of both populations.

4.6. Variability in Relation to Paleocurrent Directions of Autochthonous Unit

This section presents the results of a study concerning the influence of paleocurrent direction on lithological composition in the autochthonous unit. Out of the 55 turbidite beds that were found to display directional current structures at their base during recording of the 12 stratigraphic columns (figures 8 and 9), 28 of these were sampled and studied for their petrographic composition by modal analysis, the same samples that were used for the sake of convenience in the previous section to determine vertical petrographic variability. To portray the directional distribution for individual constituents, the relative abundances of each component were averaged for each directional class and plotted as compass roses which are shown in figure 20. The directional distribution of the relative abundances of andesite more than 300 m above the onlap surface are also included in the lower right corner of figure 20 because it was shown that these currents were not affected by the topography of the sea floor (section 2.3.4.); due to the small number of individuals in a class, however, this histogram may not be statistically meaningful.

With the exception of sporadic diabase grains, all components are fully contained within the same directional spread encompassed by the turbidity currents. They are all, more or less, equally dispersed, without any apparent dependence on paleocurrent direction, apart from slightly preferred orientations in the distribution of plutonic rock fragment and acid volcanics. The evenly distributed pattern is an indication that the exposure of rock materials was essentially uniform in the hinterland and along the length of the coast, which, in turn, implies a local source.

4.7. Roundness of Individual Components

Roundness was determined as a function of grain size for 9 different components. To ensure enough data for the less frequent constituents, it was necessary to resort to samples taken from all the sandstone units, including the Grès de St. Didier. Therefore, particularly in this study of turbidites, roundness is of little value in the determination of depositional environment. It may at best be used as a measure of the distance of transport to the basin margin prior to the sudden surge down-slope.

Roundness was estimated by visual comparison with photographic plates produced by Powers (1953). The numerical values refer to those assigned by Folk (1955), whereby the integers 1 through 6 approximately correspond to the descriptive terms "very angular", "angular", "subangular", "subrounded", "rounded", and "well rounded", respectively.

Grain size was measured in thin section along the maximum intercept across each grain. In that each specimen represents an irregular grain-size distribution traversed by a random section, only the largest particles observed in a given thin section were chosen for this purpose. Uncharacteristic, excessively large grains were ignored because it is unlikely that the largest intercept was obtained by a random section through a single suspended pebble. The procedure was repeated for a wide range of grain sizes, including conglomerates in which several thin sections were cut from the same sample. However, due to the difficulty in analyzing more than one or two pebbles per hand specimen, the gathering of data was hampered in the coarser grain sizes, in particular with regard to the less frequent components.

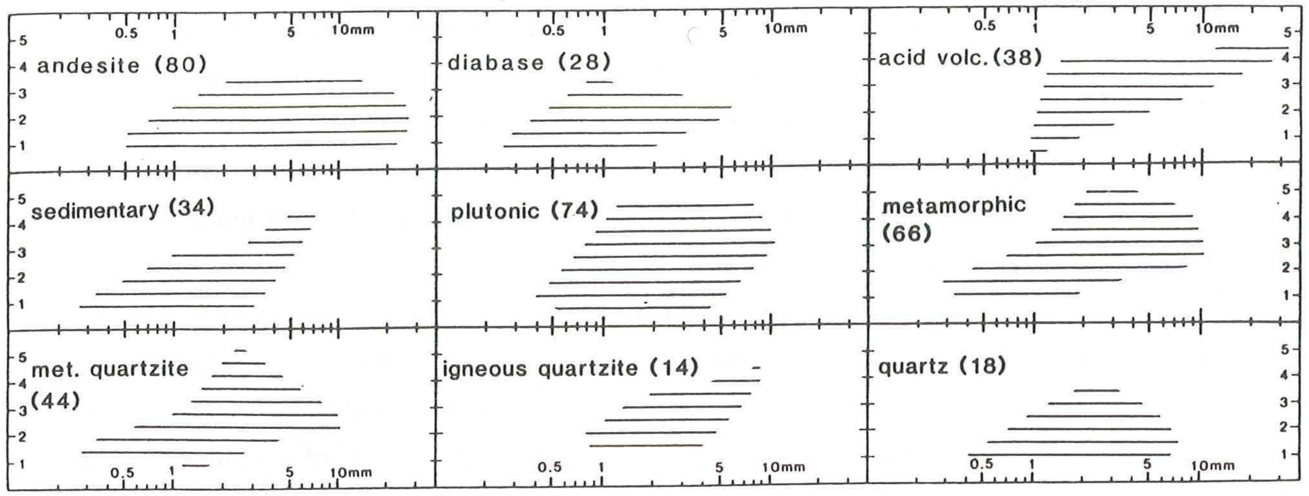


Fig. 21. Roundness plotted as a function of grain size for 9 different components. 1=very angular; 2=angular; 3=subangular; 4=subrounded; 5=rounded; 6=well rounded. Again, larger scatter is due to larger numbers (shown in parentheses) of sampled individuals in a given population.

The distribution of available data is illustrated in figure 21 where roundness is plotted against increasing grain size. The spread of measurements is generally larger for the more frequent constituents on account of the higher number of individuals in a population. Nevertheless, it is apparent that roundness is directly related to the maximum diameter of the particle. For a given component, the degree of roundness evidently shows a crude positive correlation with increasing grain size. Below approximately 0.5 mm most grains are angular or very angular, and above 5 mm they show a tendency to get rounded or subrounded, regardless of the component.

Quartz, sedimentary, andesite, and **diabase** fragments are all characterized by low values of roundness. Much of the angularity observed in **quartz** is in all probability due to its high resistance to abrasion. The angularity of **sedimentary** lithoclasts is to a large extent attributable to serrate pressure solution in carbonate fragments, and to individual particles sticking out in arenaceous grains. Similarly, the high angularity of **andesite** and, to a lesser degree, **diabase** can be partially assigned to protruding plagioclase phenocrysts. However, a short distance of transport can be inferred for the **andesite** components, irrespective of lithological considerations, in that the coarsest specimens may at times be angular up to a diameter of approximately 2.5 cm. Indications in favor of an immediate proximity come as no surprise when one considers that these are the most abundant rock fragments in the Champsaur Sandstone.

By contrast, **metamorphic** and **igneous quartzite, plutonic, metamorphic** and **acid volcanic** fragments may be characterized by higher degrees of roundness, in even the finer-grained particles. Out of all the analyzed constituents, **metamorphic quartzite** was discovered to display the highest recorded value of roundness at a diameter of 3 mm, which was estimated at 5.5. The particular circumstance that each of the better rounded components enumerated directly above could conceivably be associated with a Variscan basement massif is apparently no coincidence; it seems probable that they were eroded from a common, more distal, mostly crystalline source.

5. PROVENANCE

In essence, the clastic material contained in the Champsaur and St. Didier Sandstones may ultimately be traced back to four different parent sources: (1) andesitic volcanoes, (2) ophiolites, (3) sedimentary outcrops, and (4) a Variscan basement massif. In the following, each of these sources will be discussed individually, beginning with the immediate possibility concerning the Pelvoux Massif. In that the sedimentary rock fragments comprise a mere 1% or 2% of the average Grès du Champsaur, they are volumetrically insignificant and difficult to study. As a result, their origin was only briefly mentioned in chapter 3 and will not be considered further here. Given the insignificance of ophiolites too, it is of fundamental importance to realize that, at any one point during basin evolution, the bulk of all rock materials can be assigned to either a basement massif or andesitic source, particularly in the region of the Champsaur.

5.1. Considerations Concerning the Pelvoux Massif as a Possible Source.

An imaginable possibility concerns the adjacent Pelvoux Massif which has long been speculated to be a likely source (Termier and Lory, 1895). This is particularly thought-provoking with respect to the following points. Within the immediate reach during the Nummulitic transgression, it was unquestionably exposed and subjected to erosion, furnishing much of the clastic debris that is found in the basal conglomerate (see section 1.2.). Furthermore, by then, it had largely been stripped of its sedimentary cover - as suggested by the petrography of the Champsaur Sandstone to a similar degree. Moreover, the Pelvoux Massif is known to contain an assortment of igneous intrusive bodies which are similar to some rock types encountered in the Champsaur Sandstone, in particular rhyolitic, micrograntic, spilitic, diabase, doleritic, microdioritic and serpentinitic dikes (Vatin-Pérignon et al., 1972), in addition to extenive spilitic eruptive units found in affiliation with Triassic carbonates (Aumaitre and Buffet, 1973).

This was the reason for sampling the crystalline basement and Triassic spilites along the full length of their contact with the nummulitic transgressive sequence in the south. With regard to the granitic, gneissose, micaceous rocks, it cannot be excluded that they supplied minor amounts. On the other hand, a significant contribution by Triassic spilites may be ruled out, though they are sometimes deceivingly similar to certain diabase fragments found in the Champsaur Sandstone.

However, in the basal conglomerate described by Beuf (1959, plate 3, sample no. 3317) at the Route d'Orcières near the bridge of the Drac, spilites virtually identical to those in the Pelvoux Massif were encountered by the present author.

There is therefore little doubt that, during the initial trangressive stages onto the Pelvoux Massif, course terriginous clastics were left in the wake of retreating coastal cliffs. Nevertheless, shortly thereafter, during deposition of the Champsaur turbidites, the supply from the Pelvoux Massif is inferred to have been minimal or lacking, based on the following grounds:

1) Whereas individual rocks, such as Triassic spilites, have been detected in the basal conglomerate, they are apparently missing in the Champsaur Sandstone, as are other telltale rock types, like amphibolites and granulites, which are widespread in the Pelvoux Massif.
2) Though certain dikes and surface flows of the Pelvoux Massif (Vatin-Pérignon et al., 1972) are believed to bear some resemblance to the diabase and andesite debris of the Champsaur, their outcrop is insufficient to account for the quantities observed in the St. Champsaur Sandstone, especially with regard to the immense volume of andesites.
3) During deposition of the Champsaur turbidites, the sediment dispersal pattern was such that sands and gravels were transported from the SW (see fig. 9), i.e. from a region where the Pelvoux Massif itself cannot have been exposed (Perriaux and Uselle, 1968).
4) The high degree of roundness displayed by the crystalline components (see section 4.7.) is somewhat in contrast to what one would expect if the adjacent Pelvoux Massif were the immediate source.

It appears, then, that sands and gravels derived from the Pelvoux Massif are mostly confined to the lower bodies of rock strata. With the retreat of the shoreline during the transgression of the Nummulitic Sea, the supply of coarse clastics to a given area of the seafloor was progressively reduced prior to the deposition of the Schistes à Globigérines Formation where it is mostly subdued. Shortly before and during the influx of sandy and gravelly turbidites, the material derived from the Pelvoux Massif was in all probability largely restricted to hemipelagic, micaceous fallout.

5.2. Provenance of Ophiolites

The ophiolitic rock material contained in alpine foreland troughs comprises an association of radiolarian chert, serpentinized ultramafics, ophicalcite, chloritite, gabbro, and diabase, whereby the latter two rock types may retain a subduction-related, high-pressure metamorphic overprint with lawsonite and blue amphibole (Sawatzki, 1975; de Graciansky et al., 1971). The characteristic spectrum of ophiolite members is the justification for linking their genesis to true ophiolite suites. Furthermore, any reconstructed portrayal of outcrops must account for their occurrence along the greater part of the alpine arc. The range of ophiolite debris is as extensive as that of the andesites, namely at least 500 km, from the Upper Rhine Valley (Vuagnat, 1952) to the St. Antonin Syncline (Gabbro, Boucarut and Bodelle, 1969). For that reason, the intrusive and eruptive units of the adjacent Pelvoux Massif (Vatin-Pérignon et al., 1972) may essentially be eliminated as a major source. The outcrops are scant and sporadically disposed; they have never been affected by a high-pressure metamorphic event; nor do they comprise a real ophiolite suite; and simply because the debris shed laterally from the Pelvoux Massif is inferred to have been insignificant or lacking (see preceding section). Though ophiolites in the overlying Penninic Embrunais-Ubaye Nappes (Kerckhove, 1969) may have furnished small amounts, the present outcrops are insufficient to account for the quantities observed in the St. Didier Sandstone, nor do they lie within the structural framework of a well defined, continuous ophiolite belt. It appears, for that matter, that more internal ophiolite complexes would be more appropriate, such as the large Montgenèvre ophiolite.

It now seems acceptable that the bulk of ophiolitic debris in the Champsaur and St. Didier Sandstones was eroded from exposed Penninic thrusts (Graciansky et al., 1971), in particular from the higher units of the Prealps (Vuagnat, 1943) and the more internal Penninic zones close to the Austroalpine boundary (Vuagnat, 1952). For instance, the Gets Nappe of the Prealps (Bertrand, 1970), the Platta Nappe of the Grisons (Dietrich, 1969), the Arosa Zone of the Prätigau and Lower Engadine Window (e.g. Höck and Koller, 1987; see also Vuichard, 1984), and the Matrei Zone of the Tauern Window in the Eastern Alps (Frisch et al., 1987) include ophiolitic blocks, all in association with turbidites, either as olistostromes, wildflysch, or true mélanges. Most of these occurrences are closely affiliated with olistolitic blocs of either Austroalpine or Lower Ausroalpine derivation, and it is believed that the entire spectrum of these chaotic, ophiolite-bearing, uppermost Penninic sequences was accreted to the Austroalpine plate in the course of the Cretaceous (Waibel and Frisch, 1989).

Notwithstanding that these accreted terrains provide a plausible source, it is still poorly understood how so many ophiolites could have become concentrated in such a relatively narrow belt that extends across much of the Western and Eastern Alps. One mechanism that could account for extensive accretion or obduction of large volumes of ophiolitic rock is the arrival of a mid-oceanic ridge which, by virtue of its topographic irregularity and hot, buoyant nature would be difficult to subduct (Coleman, 1977). One must understand clearly that, by the Late Cretaceous, ophiolites were being vigorously *eroded* from the active continental margin in the Western and Eastern Alps. Firstly, there are indications that some ophiolitic *olistoliths* were derived from the south by submarine mass-gravity transport, at least in the Gets Nappe (J. Bertrand, pers. comm.). Secondly, fine-grained ophiolitic detritus is widespread in Early Upper Cretaceous flysch deposits of the Apennines and Alps. The Gosau basin of the Eastern Alps, the Verspala- and Höllentalflysch of the Arosa Zone, the Simme Flysch of the upper prealpine nappes, and the Ostia basin all contain chrom spinel as a major constiuent in their heavy mineral assemblage, with additional spilitic clasts in the Simme Flysch (Caron et al., 1979) and serpentine in the Verspala Flysch (Wildi, 1985, and references therein). Though a back-arc basin (Homewood, 1983) and intrabasinal ophiolite scarps (Homewood and Caron, 1982) have been proposed to account for this detritus, a more likely deduction is that a massive ophiolite slab was obducted onto the Austroalpine continental margin (Laubscher and Bernoulli 1982; Wildi, 1985, and references therein; Winkler, 1987). Alternatively, substantial fragments of oceanic crust could have been extensively scraped off the descending oceanic plate and incorpoarated into an accretionary prism that was uplifted and exposed to subaerial erosion by the early Late Cretaceous. Exposure of accreted oceanic sediments is known from present-day accretionary wedges that have been uplifted and emerged as islands, such as Barbados of the Carribean Arc system, the Mentawai Islands in the Sunda Arc, and Middleton Island in the Aleution Arc (Karig and Sharman, 1975). One argument on behalf of this hypothesis is the fact that detrital high-P/low-T metamorphic minerals have been discovered in Albian-Coniacian Penninic flysch deposits (Fe-glaucophane, glaucophane, crossite, and lawsonite, Winkler, 1987). This is a clear indication that (1) continental convergence was active in the earliest Cretaceous and (2) that previously subducted material was being eroded by the Late Cretaceous.

With regard to the ophiolitic material contained in the sands and gravels of the foreland, the possibility that it was at least partially derived from an obducted ophiolite slab or back-arc basin deserves our serious consideration. Either possibility could account for the peculiar lack of clastics derived from the Schistes Lustrés (Vuagnat, 1952) with which the present internal outcrops are widely associated. On the other hand, the occasional occurrence of high-pressure metamorphic assemblages in mafic cobbles (Graciansky et al., 1971; Sawatzki, 1975) indicates that uplifted accreted terrains definitely contributed as a source. In any case, the fact that the associated andesite cobbles were never affected by such a subduction-related metamorphism suggests that the ophiolites do not represent portions of oceanic crust that supported an overlying andesitic island-arc as repeatedly taken into consideration by Vuagnat (1943, 1952, 1985).

5.3. Provenance of Andesites

In view of the (1) calc-alkaline nature of the andesite cobbles, (2) their widespread curvilinear occurrence adjacent and parallel to a plate boundary (see Elter et al., 1969; Stalder, 1979; Vuagnat, 1985), and (3) their appearence during a convergent episode, there is ample justification for relating their origin to a subduction zone and associated magmatic arc. However, in the light of prevailing plate-tectonic theories, the unreasonably late emergence of andesitic volcanoes in the Eocene has been assumed to be something of a mystery, particularly with regard to the recent realization that the onset of continental convergence should be assigned to the earliest Cretaceous (Winkler, 1987). Nevertheless, the timing and distribution of andesitic activity in the Western Alps, the Northern Apennines, southern Italy and Sicily become apparent when one considers what effect the relative plate motions between Europe and Africa (Dewey et al., 1973) must have had on the western edge of Adria and, for that matter, on differently trending segments of the Adriatic plate. The geometric outline of Adria's plate boundaries is such that its initial eastward drift relative to Europe during the Jurassic and much of the Cretaceous must have resulted in (1) active sea-floor spreading behind its N-S trending trailing edge in the west, (2) mostly left-lateral strike-slip motion along its E-W aligned margin in the Eastern Alps and Western Carpathians, and (3) continental convergence in the Eastern Carpathians, where the plate boundary was oriented N-S as well. In the Eastern Carpathians, Upper Jurassic volcanic activity and deformation of the adjacent flysch trough from at least the Albian onwards attest to the strongly compressive resultant at its leading edge in the east (Hesse, 1981, 1982). During the Late Cretaceous, the original, W-E directed motion of the Adriatic plate was abruptly reversed. Consequently, in the Eastern Alps and Western Carpathians, the dominant strike-slip movement was largely maintained, but in the opposite sense, whereby compressive resultants and associated eo-Alpine metamorphic events were restricted to irregularities along its northern edge (Waibel and Frisch, 1989); subduction was initiated at its formerly passive margin in the west, which, by the Late Eocene, ultimately led to the generation of andesitic volcanism, simultaneously in the Western Alps, the Northern Apennines, southern Italy and Sicily. The sporadic but widespread occurrence of this volcanism along more than a thousand kilometers of Adria's western edge strongly suggests that, irrespective of paleomagnetic considerations (Dewey et al., 1973), it was generated in response to Adria's drift toward the west. Whereas the ensuing N-S compressional movements between Europe and Africa resulted in the formation of abundant Neogene volcanic activity in the Inner Carpathians, no such volcanism was generated in the Eastern Alps, where subduction presumably did not reach great enough depths (Hesse, 1982). In view of the dominant strike-slip motion throughout the prior history of the Eastern Alps, it is assumed that, once a strongly compressive resultant was finally established, the initial width of the basin fell short of the minimum value the oceanic lithosphere would have required to reach the critical depth. In that the initial long-lived eastward movement of the Adriatic plate must have left a sizeable ocean basin in its wake, large volumes of lithospheric material were potentially available for subduction and magma generation, and this ultimately led to the laterally most extensively preserved calc-alkaline volcanic activity at its western edge.

The study of this ancient arc is largely confined to the sporadic, epiclastic, andesitic debris contained in the network of Tertiary foreland basins. The original flows have completely vanished, either by erosion or subduction, or because they now lie safely buried under a thick sedimentary cover or tectonic nappe (Vuagnat, 1952). M. Vuagnat (pers. comm.) concedes that - to his knowledge - no such eruptive units have as yet been found that fully satisfy the requirements concerning age, petrographic and geochemical characteristics, structural position, and so on. The remnants of volcanic flows described by Barbier and Michel (1958) in the Flysch des Aiguilles d'Arves bear little petrographic resemblance to the Taveyanne andesites (Vuagnat 1985), and are in reality more acidic (Bocquet and Michel 1966, in Martini and Vuagnat, 1967). Though the volcanism to the NE of Fréjus in the Estérel Massif is calc-alkaline and oligocene in age, it mainly comprises qu-bearing microdiorites; other volcanic occurrences in southeastern France are mostly younger (Miocene-Pliocene) and predominantly alkaline (Baubron 1984).

A comprehensive review of the Taveyanne Sandstone is given by Vuagnat (1985) who rediscusses the possibility previously considered by de Quervain (1928) that the Taveyanne volcanism is genetically coupled with the emplacement of Periadriatic plutons in the Southern Alps. He stresses that the andesite veins associated with the Val Bregaglia Pluton are actually somewhat younger. On the other hand, he admits that the andesites of the Taveyanne Sandstone and the Periadriatic plutons possibly form part of the same orogenic episode, in which andesitic surface flows preceded the emplacement of granitic intrusives (see also Hsü and Schlanger, 1971). Such a genetic relationship now seems likely in view of the coincident ages that have recently been determined from andesitic cobbles in the St. Antonin Syncline, which have been dated independantly at 33.9 +- 1.5 Ma (Baubron and Cavelier, 1982, in Pairis et al., 1984) and 31.7 +- 0.8 Ma (Fontignie and Waibel, in prep.). Excluding the samples that have been appreciably affected by subsequent metamorphism (Fontignie, 1981; see also discussion by Vuagnat, 1985), these are the youngest *reliable* K/Ar whole-rock isochron datings that have been determined in Taveyanne-similar rocks so far. They fall close to those determined for the Bergell Pluton (30 Ma, Gulson 1973) and the andesites of the Sesia Zone (29-33 Ma, Scheuring et al., 1974). Nevertheless, the bulk of the Taveyanne volcanism remains older than the discordant Periadriatic intrusive bodies. This is consistent with the recognition that, in mountain belts, orogenic andesites commonly predate the episode of intense deformation associated with continental collision (Gill, 1982).

Apart from the workers who believe to have perceived traces of concurrent volcanic activity in or near the depositional basin (Termier and Lory, 1895; Bellair 1957; Beuf, 1959; Beuf et al., 1961; Didier and Lameyre 1978; Giraud 1983; Doudoux et al., 1987), most authors working with the Taveyanne Sandstone agree that the andesitic volcanoes were originally erected in the immediate vicinity of a subduction zone, then detached from their foundation in the course of continental collision, incorporated into one or several nappes, and transported to the basin margin in the foreland, away from the orogenic belt (e.g. Vuagnat 1952, 1985; Sawatzki, 1975). For the time being, potassium-argon age determinations cannot resolve whether the lava flows were originally erupted in the proximity of the depositional basin, or wether there was sufficient time to allow for long distances of tectonic transport to their ultimate site of deposition; due to the effects of argon over-pressure, only *maximum* ages may be estimated, which are close to the stratigraphic age or older (43,5 +- 4.3 Ma in the Taveyanne Sandtone, Fontignie, 1980; 37.6 +- 1.3 Ma and 40.2 +- 1.3 Ma in the Champsaur Sandstone, Fontignie et al., 1987; 33.9 +- 1.5 Ma, Baubron and Cavelier, 1982, in Pairis et al., 1984, and 34.4 +- 3.4 Ma, Fontignie and Waibel, in prep., in the St. Antonin Syncline). However, in analogy to present-day convergent margins, it is thought that the andesitic volcanoes were originally situated at the southernmost limit of the Penninic realm (Martini and Vuagnat, 1967; Coombs et al., 1976) to eventually occupy a structural position above the Upper Prealpine Nappes (Elter et al., 1969). As yet, it is not known with certainty whether they formed part of an intraoceanic or continental arc.

Note that, if either of these two possibilities is correct, the andesitic nappe or nappes must have been far removed from their original foundation by the time they reached the autochthonous foreland. During deposition of the Taveyanne and Champsaur Sandstones, the greater part of coarse parent rock materials was derived from an andesitic source (up to 90%), and it may reasonably be assumed that the andesitic rocks were exposed somewhere in the immediate hinterland and along the length of the coast. From this it follows that, during deposition of the volcaniclastic graywackes, the andesitic source was in a structural position at or near sea level. Furthermore, since the graywackes transgress onto the autochthonous, the andesites must have been at a structural level, say, only 1000 m (section 2.3.6.) above the stable foreland, which corresponds to the estimated depth of the Nummulitic Sea. It will be appreciated that, throughout the deposition of the Taveyanne and Champsaur Sandstones, they cannot have occupied a structural position above the entire stack of accreted Penninic thrusts, much less the Austroalpine nappes. If, originally, the volcanoes were truely situated somewhere near the Penninic/Austroalpine boundary, they must have been thrust over the Penninic units before sliding down to their frontal position in the foreland, perhaps gravitationally. Emplacement of an andesitic nappe by long-distance overthrusting and/or gravitiy sliding is not required if, alternatively, eruption of the andesitic flows initially occurred closer to the depositional basin in the foreland, in a region neighboring the Ultrahelvetic Zone and lower Penninic nappes. In either circumstance, erosion of the flows must have taken place between the basin margin and the front of the approaching Penninic nappes -provided that (1) they were situated on the internal side of the Nummulitic Sea and (2) immediately above the stable foreland as argued above. Supposing that the frontal penninic nappes were still deep in the hinterland during deposition of the andesitic sequences, excessively long distances of fluvial transport could inhibit the supply of such debris, apart from evasive sand-sized particles. The progressive but subtle rise in the amount of associated ophiolite debris may reflect the gradual advance and emergence of the more internal units with the passage of time. However, considering that, in the Western Alps, the uppermost nummulitic thrusts are directly overlain by the Embrunais-Ubaye Nappes, the andesitic flows must have been completely eroded prior to the emplacement of these units; on the other hand, they might have been entirely overrun and buried by these internal thrusts.

5.4. Which Variscan Basement Massif?

Apart from the massive interspersal of andesites, the greater part of the remaining rock material can be ascribed to a near-by crystalline source. Including the less obvious components that are thought to be related to a basement complex, such as acid volcanics, it is estimated that, on average, the sandstones of unit I comprise 95% of these rocks, if not more. Any paleogeographic reconstruction must therefore make allowance for an extensive Variscan basement massif in the immediate vicinity of the Champsaur. Accepting the inference that substantial contributions from the adjacent Pelvoux Massif may essentially be ruled out (section 5.1), we are unfortunately deprived of the most likely source. This is all the more disappointing in view of the fact that course sands and gravels were dispersed from the SW (fig. 9) where currently no crystalline massif is exposed (Perriaux and Uselle, 1968).

Yet it is fairly clear that the granitic rock masses should be searched for on the side of the sedimentary basin away from the direction of thrusting. Numerous lines of evidence have led to the deduction that, in the depressions of the fold- and thrust belt, the sedimentary infill was for the most part derived from internal terrains (de Quervain, 1928; Vuagnat, 1952). The general deficiency of basement rock materials exposed on the external side of the Champsaur and St. Didier Sandtones confirms the validity of this assumption, at least in the region of the Dauphiné. Whole-rock K/Ar isochron datings on some granitic pebbles contained in the Champsaur Sandstone indicate that these rocks were derived from plutons that were emplaced at least 122-260 Ma ago (Fontignie et al., 1987). This clearly excludes a genetic relationship with alpine intrusive bodies situated along the Periadriatic Fault. Rather, it may reasonably be assumed that such minimum ages corresond to Variscan episodes. Although it is generally thought that substantial amounts of terrigenous clastics were supplied to the Annot Sandstone from the Corsica-Sardinia landmass (Kuenen et al., 1957; Stanley and Mutti, 1968; Ivaldi, 1974) prior to its counter-clockwise rotation in Miocene times (Alvarez, 1972), the invariably proximal development of the Champsaur Sandstone excludes the unreasonably long distance of longitudinal transport required from this potential source.

This leaves us with three concentric belts in which suitable Variscan outcrops are known to occur along segments of the alpine arc: (1) the external, mostly autochthonous crystalline massifs (Boussac, 1912; Vuagnat, 1952; Stanley, 1961); (2) a multitude of internal crystalline massifs intermittently embedded in disrupted Penninic flysch sequences (Vuagnat, 1952), debatably of either mid-Penninic, Lower Austroalpine, or Austroalpine derivation; and (3) the extensive Austroalpine basement complex which has since been largely unroofed in vast areas of the Western Alps. Conceding that, for each and every sandstone unit in the Champsaur, the granitic supply from facies belts (2) and (3) cannot be excluded altogether, it is felt that quantities received from these sources are insignificant, particularly in unit I where they, for all one knows, might be truely lacking. Firstly, the present Penninic outcrops of granitic rock bodies are insufficient to account for the sizeable quantities observed in the Champsaur, and they have often been overprinted by alpine metamorphic assembages acquired during accretion of the enclosing sediments. Secondly, for both the Penninic and Austroalpine basement rocks, it is difficult to envisage a suitable mechanism that could transport this debris without incorporating significant amounts of the intervening Penninic sediments in transit, which are obviously deficient in the Champsaur Sandstone. The fact that the crystalline massif supplying unit I was mechanically disintegrated and redeposited with negligible dilution by other components is strongly indicative of a *local* source. Thirdly, by reasoning similar to that exercised in the preceding section, it may be argued that, during deposition of the Champsaur Sandstone, the crystalline basement must have been close to sea level and the stable foreland, and thus in no tectonic position that would allow for Penninic subsurface structures thousands of meters thick. There is therefore little doubt that the granitic components were for the most part shed from an external crystalline massif that was located to the SE of the Champsaur, on the internal side of the sedimentary basin, in a region now deeply buried by Penninic thrusts.

Several external crystalline massifs presently occupy a similar, more internal position with respect to the lateral equivalents of the Champsaur Sandstone, namely the Mont Blanc-Aiguilles Rouges and Aar-Gothard Massifs to the S of the Taveyanne Sandstone, and the Argentera-Mercantour Massif to the E of the Annot Sandstone. However it is as yet entirely doubtful whether these massifs, as currently exposed, actually supplied material to the adjacent troughs. When the highest Helvetic and Ultrahelvetic thrusts and recumbent folds are unrolled to their original position, it is apparent that the Taveyanne Sandstone of the Morcles Nappe (Martini, 1968) was originally depositied to the south of the exposed Mont blanc-Aiguilles Rouges Massif, i.e. on its immediate Mesozoic sedimentary cover (see figure 3 by Ramsay et al., 1985), which is quite comparable to the present configuration of outcrops in the Champsaur. Assuming that the sedimentary fill was introduced to the trough from the south, Vuagnat (1952) considered the possibilty that granitic detritus in the Taveyanne Sandstone was derived from a hidden area to the south of the Mont blanc-Aiguilles Rouges and Aar-Gothard Massifs. Similarly, recent studies have shown that certain rock types characteristic of the Argentera-Mercantour Massif are missing in the Annot Sandstone, and there is mounting evidence that uplift of this massif occurred after deposition of these sediments (Apps and Ghibaudo, 1985; Elliot and Graham, 1985).

The question arises whether crystalline components received by these troughs should be partially ascribed to one and the same system of Variscan basement massifs currently covered by Penninic nappes, and whether regional exposures were more or less continuous between the Central and Western Alps. The hypothetical Variscan belt would have to be positioned intermittently under the edge of the present Penninic erosional front, adjacent and parallel to the curvilinear outcrop pattern delineated by the Aar-Gothard, Mont Blanc-Aiguilles Rouges, Belledonne-Pelvoux, and Argentera-Mercantour massifs, in a region corresponding to the innermost limit of the Helvetic realm. Extensive Variscan basement massifs presumably appeared early in this area, in view of the coarse granitic material that was vastly eroded and slumped down from the edge of the European continental margin during the first formation of oceanic crust since the Early Jurassic (see Gruner, 1981; also Lemoine et al., 1981). Personally, it is believed that, as yet, no suitable alternatives have been proposed to account for the provenance of granitic sands in the Champsaur and Taveyanne Sandstones. Notwithstanding that the Annot Sandstone partially embodies detritus derived from the Corsica-Sardinia landmass in the south (Kuenen et al., 1957; Stanley and Mutti, 1968; Ivaldi, 1974), its outcrops farther to the north of the Mediterranean Sea should be reexamined in the light of this hypothesis, in particular where the Nummulitic transgresses directly onto Mesozoic sediments in the thin band of outcrops that borders the Argentera-Mercantour massif to the E and NE.

6. METAMORPHISM

6.1. INTRODUCTION

6.1.1. General Context

Due to the absence of penetrative deformational fabrics, the secondary mineral associations that characterize the volcaniclastic graywackes of the external Alps were for many years thought to arise from weathering or alterations occurring soon after the deposition of these rocks (De Quervain, 1928; Vuagnat, 1952). With the discovery of relict calcic plagioclase in the course of Martini's thesis (1968), it was recognized that the spilitic nature of the andesites was by no means primary, and the secondary assemblages were quickly reinterpreted in the light of Coombs' work (1960, 1961) as having resulted from incipient "burial" metamorphism of regional extent (Martini and Vuagnat, 1965). Whereas in many mountain belts the gradual rise in temperature was generated by the rapid accumulation of thick geosynclinal sedimentary sequences, or by the heat surrounding intrusive bodies, in the external Alps the rise in temperature has been attributed to partial subduction and thrust loading by the Prealps and higher Helvetic-Ultrahelvetic nappes (Kübler et al., 1974). The recognition of regional metamorphism beyond the traditional confines of the Penninic facies belt opened a new field in alpine geology, and numerous studies have been devoted to the Taveyanne Sandstone and associated rocks ever since. Emphasis has been on mineral assemblages (Sawatzki and Vuagnat, 1971; Sawatzki, 1975; Bussy and Epard, 1984), coal rank (Stalder, 1979; Kisch, 1980), chemical mineralogy (Coombs et al., 1976), fluid inclusions in fissure quartz (for references, see Mullis, 1987), and clay mineral contents (Kübler, 1973a; Aprahamian, 1974; Sawatzki, 1975; Stalder, 1979; Lippmann and Rothfuss, 1980).

Regional metamorphic zonations have been delineated on the basis of diagnostic mineral associations in the Alps of Switzerland and Savoie, where metamorphic grade increases progressively from W to E along the alpine arc, and from N to S in a given transverse (Kübler et al., 1974). Also, due to the early precipitation of minerals which inhibit the transmission of reactive solutions through pore spaces, the regional patterns portray the characteristic persistence of metastable phases (Cho et al., 1986) and overlapping (Coombs, 1971) of metamorphic zones. Nevertheless, the distribution of mineral assemblages in the Taveyanne Sandstone crudely displays a complete transition from diagenesis to greenschist facies metamorphism; ideally, it comprises the following sequence:

- **heulandite zone** (Sawatzki and Vuagnat, 1971; Sawatzki, 1975);
- **laumontite zone** (Sawatzki and Vuagnat, 1971; Sawatzki, 1975; Martini and Vuagnat, 1965; Martini, 1968; Bussy and Epard, 1984);
- **prehnite-pumpellyite zone** (Sawatzki and Vuagnat, 1971; Sawatzki, 1975 Martini and Vuagnat, 1965; Martini, 1968; Bussy and Epard, 1984);
- **pumpellyite-actinolite zone** (Coombs et al., 1976; Bussy and Epard, 1984);
- **actinolite-epidote zone** (Bussy and Epard, 1984)

A comprehensive metamorphic study of the Taveyanne Sanstone and its lateral equivalents in the Western Alps, the Northern Apennines, southern Italy and Sicily was undertaken by Stalder (1979) who established links between fixed carbon, illite "crystallinity", shale density, sandstone porosity, and characteristic mineral assemblages in most of these zones.

A cursory examination of the Champsaur Sandstone by Martini and Vuagnat (1965) initially revealed the existence of laumontite. Subsequently, prehnite, pumpellyite, epidote, and corrensite were additionally detected by Stalder (1979) and listed in sections 10-12 of table 1. In the present study, however, the volcaniclastic graywackes were found to be largely devoid of epidote, apart from scattered detrital grains and clustered aggregates ocurring in granitic pebbles which are thought to reflect the parent rock. In the entire thin-section study, only a few crystals or replacement masses of epidote were considered to be of metamorphic origin, and these were mostly found in reaction zones adjacent to fissures within the host rock. Similarly, corrensite was not detected in oriented glycolated and heated slide mounts of clay fractions which were separated from arenaceous rocks. Though corrensite was also detected by Aprahamian (1974), it is possible that these occurrences are relict and that, with rising temperature, they were finally at the verge of being decomposed.

The secondary mineral associations of the Chapsaur Sandstone are thus characteristic of the transition from zeolite- to prehnite-pumpellyite facies assemblages in the external Alps. They are most comparable to those observed at Audon in the Diablerets Nappe (Bussy and Epard, 1984), in vast areas of the Morcles Nappe (Martini, 1968), and in the northeastern sector of the Thônes Syncline (Sawatzki and Vuagnat, 1971), though in these occurrences some of the phases may be bound to the vicinity fissures or shear zones. In the Champsaur Sandstone, two local assemblages are irregularly disposed side-by-side, one in which calc-silicates comprise the dominant secondary constituents, and another in which the diagnostic calc-silicates are suppressed by calcite, like in most occurences of the Taveyanne Sandstone, irrespective of rank. It will be shown that the irregular distribution of these facies is strongly dependent on the variable composition of the fluid phase, in particular the localized liberation of CO_2 in the vicinity of carbonates and marls. The mottled laumontite facies of the Champsaur Sandstone is commonly carbonate-free. It originated under conditions permitting the formation of secondary laumontite, pumpellyite, and prehnite; primary augite and hornblende are strongly altered but still largely preserved. Throughout the second, petrogenetically less diagnostic, "vert facies", calcite has inhibited the formation of these calc-silicates, and the primary ferromagnesian minerals have been largely replaced but may persist.

6.1.2. Areal Distribution of the Metamorphic Facies in the Champsaur

The two metamorphic facies briefly outlined above are confined to strata of appropriate bulk composition. They are thus restricted to sandstone unit 3a, its two subunits (3b and 3c), and the westernmost portion of unit 2a, where the percentage of inherently unstable andesite debris is sufficiently high (section 4.3) to have brought about reactions involving these constituents (fig. 3). For both metamorphic facies, the mineral associations remain essentially the same and their distribution is more or less homogeneous throughout the sandstone bodies of these units. Due to the limited stratigraphic thickness and modest areal extent of volcaniclastic outcrops, no metamorphic zonations were detected in the Champsaur, neither vertically nor laterally.

Given the large and rapid variance in the amount of andesitic clasts between successive sandstone units and subunits (section 4.4.), the Champsaur Sandstone provides an opportunity to determine the appearence of metamorphic assemblages as a function of gross lithological composition - if one may rightfully assume that the P/T regime was essentially uniform over such a restricted area. The minimum amount of andesite required to give rise to metamorphic reactions is defined by the absence of secondary calc-silicates in the sandstone bodies containing the highest percentages of andesitic debris. The lowermost limit is prescribed by sandstone unit 2b and the northeastern portion of unit 2a, both of which contain approximately 30% (And=15%; Plag=15%) on average; the absence of secondary calc-silicates was confirmed with the petrographic microscope and a staining technique (see below) on individual samples comprising up to 37% (And=19%; Plag=18%). The primary chemical controlling factor for the initiation of zeolite-facies metamorphism is apparently not the number of contacts between potential reactants. Firstly, such high proportions of andesitic constituents should at least ensure the required contacts around some of the mafic grains. Secondly, metamorphic assemblages have been formed in individual graywacke beds of comparable lithological composition throughout the autochthonous unit. It appears, then, that in an appropriate P/T field, the initial onset of zeolite-facies metamorphism is not necessarily dependent on the chemical characteristics of a given specimen, but on the overall composition of entire bodies of strata. During very-low-grade metamorphism of the Champsaur graywackes, uninhibited circulation of hydrothermal solutions was apparently essential for the transfer and exchange of components over larger volumes of rock. It is interesting to note that diabase fragments apparently did not contribute much to the required bulk composition of the metamorphosed rocks. The occasional fragments encountered in this study were found to be largely devoid of secondary calc-silicates. The general persistence of diabase fragments is presumably related to the liberation of essential lime during a previous ocean-floor metamorphism or eo-alpine metamorphic episode.

6.1.3. The Briones Sandstone, California

The Champsaur Sandstones are customarily called "Grès Mouchetés" (Mottled Sandstones) on account of the peculiar mottled appearance laumontite may produce in these rocks, which is a common and distinctive feature of many laumontitized sandstones occurring the world over. The spotty development of laumontite in Taringatura, southern New Zealand, has been compared to the mottled laumontite facies of the external Alps (Coombs, 1971) which, in turn, has been likened to similar occurrences in Jugoslavia (Obradovic and Pavlovic, 1975, 1976), Alaska (Hoare et al., 1964), and California (Madsen and Murata, 1970) (Lippmann and Rothfuss, 1980). To the author's surprise, the latter occurrence was found to be conveniently located within 15 miles of his parents' residence in Fremont, California. During an extended visit, the opportunity was taken to sample the Briones Sandstone along Penitencia Creek of Alum Rock Park, in the Diablo Range near San José, California, for the purpose of basic comparison. Similarities or differences with the Champsaur Sandstone are briefly mentioned in passing throughout the following sections; for easy reference, **Briones Sandstone** is highlighted in bold.

The occurrence of the Briones Sandstone was mapped and its gross lithological characteristics described by Crittenden (1951). In a more recent study, it was shown to contain zeolite-facies assemblages by Madsen and Murata (1970) who give a comprehensive account of its alteration products, with emphasis on the distribution, characterization, and genesis of laumontite. The Briones Sandstone comprises a sequence of predominantly massive, thick-bedded, medium- to coarse-grained, arckosic sandstones of late Miocene age, which is locally 5000 ft thick. The sandstones contain variable amounts of detrital quartz, feldspar, biotite, hornblende, glauconite, chert, limestone, abundant shells, and minor plant and wood fragments; they may contain substantial amounts of andesite fragments - up to 50% by volume - in addition to subordinate amounts of arborescent and spherulitic diabase grains. Apart from secondary albite-oligoclase, laumontite is the most prominent constituent of the alteration products. In the absence of calcite, it formed in the middle and upper part of the sedimentary sequence, where it occurs as interstitial cement, replaces plagioclase, and fills veins. Clinoptilite and, in individual fractures, stilbite are confined to the upper part of the sequence, indicating a rudimentary depth zonation. Chlorite is abundant in the lowermost portion of the Briones Sandstone, and progressively gives way to montmorillonite at the top. Where the primary calcic plagioclase is locally preserved, it is in the compositional range of oligoclase-andesine.

6.2. The Mottled Laumontite Facies

The Champsaur Sandstone clearly displays the antipathetic relationship between calcite and calc-silicates that commonly characterizes incipiently metamorphosed rocks, either because early, interstitial precipitation of calcite inhibits the transmission of aqueous solutions (Martini and Vuagnat, 1967; Madsen and Murata, 1970; Sawatzki, 1975; Stalder, 1979) or because the associated rise in the activity of CO_2 significantly reduces the stability of zeolite facies assemblages (e.g. Coombs, 1971). In the presence of calcite, the "vert facies" is formed instead and described in great length below. Consequently, among the sandstone units of appropriate composition (section 6.1.2.), the zeolite facies assemblages occur only in specimens that are devoid or nearly devoid of calcite. They are thus usually suppressed in the immediate vicinity of marly shale partings and rip-up clasts, and occassionally in the neighborhood of nummulitic limestones and local faults, where calcite pervades the rock.

Even in the absence of calcite, small-scale variations in permeability can sometimes affect the local development of assemblages. Permeability obstacles formed by pebbles and cobbles may result in the exclusion of laumontite and possibly pumpellyite and prehnite from larger andesite fragments (see table III), so these minerals may be more evenly distributed in finer-grained rocks. On the other hand, chlorite and, rarely, pumpellyite are occasionally concentrated as alteration products along anastomosing surfaces that are crudely aligned parallel to the local pattern of veins, suggesting that reactive solutions were able to diffuse more freely along restricted zones of weakness, yet mostly without any apparent openings or displacements in the affected portions of the rock. The profound influence of freely circulating fluids is best illustrated by the deviation of assemblages in fracture fillings and adjacent reaction zones within the host rock (section 6.2.8.).

Table V. Assemblages of mottled laumontite-facies rocks.

sample	Laumontite	Pyroxene	Amphibole	Chlorite	Sphene	Prehnite	Pumpellyite	Sericite	Calcite	zoned Plag
11	?	X	X	X	X	?	?	(X)	---	---
33	X	X	---	X	X	---	X	(---)	---	---
76	X	X	---	X	X	(X)	X	---	---	---
77	X	X	---	X	X	X	X	---	---	---
80	?	X	---	X	X	---	?	(X)	---	---
88	X	X	---	X	X	---	X	---	---	---
107	X	X	(X)	X	X	X	X	(X)	---	---
113	X	X	X	X	X	X	X	---	---	---
115	X	(---)	X	X	X	X	---	---	---	---
116	X	X	X	X	X	---	---	---	(X)	---
117	X	X	X	X	X	---	---	(X)	---	---
120	X	X	X	X	X	---	---	(X)	(X)	---
145	X	X	---	X	X	X	X	---	---	---
159	X	X	---	X	X	X	X	(X)	---	---
165	X	---	---	X	X	X	---	(---)	---	---
166	X	X	---	X	X	X	X	---	X	---
173	X	X	X	X	X	---	?	(X)	---	---
202	---	X	---	X	X	X	X	---	---	---
203	X	X	(X)	X	X	X	X	---	---	---
204	X	X	X	X	X	X	X	---	X	---
205	X	X	---	X	X	X	X	---	---	---
206	X	X	---	X	X	X	X	---	X	---
224	X	X	X	X	X	X	X	X	---	---

··· = none; (···) = negligible; (X) = minor; X = major; ? = doubtful

The mineral associations of the Champsaur Sandstone are transitional between those that commonly characterize zeolite- and prehnite-pumpellyite facies rocks. Relevant alteration processes are extensive albitization, laumontitization, chloritization, and minor sericitization, accompanied by newly formed pumpellyite, prehnite and sphene; primary pyroxene and amphibole, where present, are largely preserved (Table V), though they may be incipiently or wholly replaced by chlorite, particularly the former.

6.2.1. Laumontite

6.2.1.1. Analytical methods

Laumontite was identified by x-ray analysis of light-mineral fractions that were separated by conventional methods from crushed sandstone specimens; no heulandite or other relict zeolite minerals were detected by this method (cf. Sawatzki and Vuagnat, 1971; Sawatzki, 1975). When moderately heated (as during thin-section preparation) or exposed to the atmosphere, laumontite ($CaAl_2Si_4O_{12}.4H_2O$) is quickly converted to leonhardite ($CaAl_2SiO_{12}3.5H_2O$) by partial dehydration, a transformation which is easily reversible (Coombs, 1952; Kaley and Hanson, 1955; Lapham, 1963; Gilbert, 1951). X-ray diffraction patterns were therefore obtained from 2 sets of differently treated powders, one in which the samples were oven-dried at 110°C for approximately 2 hours, the other after saturation with water. In the latter procedure, the samples were soaked in water overnight, then mounted and analyzed after allowing the excess water to evaporate, but before the appearance of dessication cracks. The d spacings and intensities arrived at (using a Philips x-ray difractometer and CuKa radiation) are listed in table VI and compared to the values determined by Madsen and Murata (1979) and Coombs (1952).

The microscopic study of laumontite was made much easier by an effective staining technique which renders it more recognizable in thin section (Madsen and Murata, 1970):

> "The method entails immersing the thin section or finely polished (400-mesh abrasive powder) slab of rock in a tepid (40°C) solution of oxalic acid (about 10 parts of $H_2C_2O_4.2H_2O$ in 100 parts water) for 4 minutes and then thoroughly rinsing the rock with distilled water and drying it.
>
> Oxalic acid liberates calcium from laumontite, either through cation exchange or direct decomposition, but not from plagioclase, clinoptilolite, stilbite, lawsonite, or calcite. The liberated calcium combines with the acid to form an adherent white deposit of finely crystallized calcium oxalate on the surface of laumontite... It is best to treat only a part of a section with the oxalic acid solution. The cover glass should be affixed with care to avoid dislodging the oxalate deposit."

Experience by the present writer has shown that, when viewed between parallel polars in plane-polarized light, the oxalate deposit is more easily recognizable without the cover glass, which however hampers the study of other minerals present in a given thin section. For that reason, the thin section under

Table VI. X-ray diffraction data for laumontite and leohardite (d in angstroms).

LEONHARDITE								LAUMONTITE			
Madsen and Murata, 1970				Coombs, 1952		this study		this study		Coombs, 1952	
hkl	d, calculated	d, observed	I	d	I	d	I	d	I	d	I
110	9.44	9.44	100	--	--	9.44	100	9.50	78	--	--
001	7.01	--	--	--	--	--	--	--	--	--	--
200	6.83	6.83	75	6.88	60	6.82	68	6.50	83	6.97	60
020	6.53	--	--	--	--	--	--	--	--	--	--
$\bar{1}11$	6.49	--	--	--	--	--	--	--	--	--	--
$\bar{2}01$	6.18	6.18	10	6.21	20	6.18	12	6.14	17	6.16	10
111	5.041	5.040	20	5.07	20	5.02	10	5.16	22	5.14	10
021	4.779	--	--	--	--	--	--	--	--	--	--
220	4.722	4.724	14	4.75	10	4.72	15	4.80	32	4.77	20
$\bar{2}21$	4.490	4.489	22	4.51	30	4.49	19	4.50	28	4.50	10
$\bar{3}11$	4.427	--	--	--	--	--	--	--	--	--	--
310	4.300	4.300	1	--	--	--	--	--	--	--	--
201	4.174	--	--								
130	4.150	4.149	100	4.18	100	4.15	60	4.21	80	4.18	100
$\bar{1}31$	3.763	3.767	18	3.77	<10	3.77	22	3.78	53	3.76	<10
$\bar{2}02$	3.736	--	--	--	--	--	--	--	--	--	--
$\bar{4}01$	3.654	3.654	56	3.67	40	3.67	41	3.67	100	3.67	40
$\bar{1}12$	3.603	--	--	--	--	--	--	--	--	--	--
221	3.518	--	--								
002	3.504	3.505	60	3.52	100	3.50	56	3.54	53	3.53	60
400	3.415										
131	3.406	3.407	16	3.42	<10	3.39	5	3.41	3	3.45	10
$\bar{3}12$	3.358	3.358	40	3.36	10	3.36	20	3.35	22	3.35	20
040	3.267	3.267	60	3.28	30	3.27	16	3.30	83	3.29	30
$\bar{2}22$	3.243	--	--	--	--	--	--	--	--	--	--
311	3.197	--	--								
$\bar{3}31$	3.196	3.194	60	3.21	20	3.21	25	3.21	24	3.21	30
$\bar{4}21$	3.189	--	--								
330	3.148	3.148	32	3.16	10	3.15	22	3.19	13	3.19	10
$\bar{4}02$	3.090	--	--	3.09	<10	--	--	--	--	--	--
022	3.088	--	--	--	--	--	--	--	--	--	--
112	3.040	--	--								
420	3.027	3.027	40	3.04	40	3.03	20	3.09	55	3.08	40
041	2.961										
240	2.947	2.900	4	2.95	<10	2.93	7	2.97	30	2.97	<10
$\bar{2}41$	2.888	--	--	--	--	--	--	--	--	--	--
$\bar{5}11$	2.873	2.873	25	2.88	30	2.88	14	2.90	63	2.89	30
$\bar{1}32$	2.841	--	--	--	--	--	--	--	--	--	--
$\bar{4}22$	2.793	2.790	22	2.80	20	2.79	11	2.78	22	2.78	20
202	2.731	--	--	2.73	<10	--	--	--	--	2.61	30
$\bar{3}32$	2.716	--	--	--	--	--	--	--	--	--	--
401	2.699	--	--	--	--	--	--	--	--	--	--
510	2.674	--	--	--	--	--	--	--	--	--	--
$\bar{5}12$	2.642	2.641	4	2.64	<10	2.63	4	2.60	8	2.60	10
331	2.629	2.628	1	--	--	--	--	--	--	--	--
241	2.573	2.571	30	2.58	3	2.55	18	2.55	36	2.51	<10

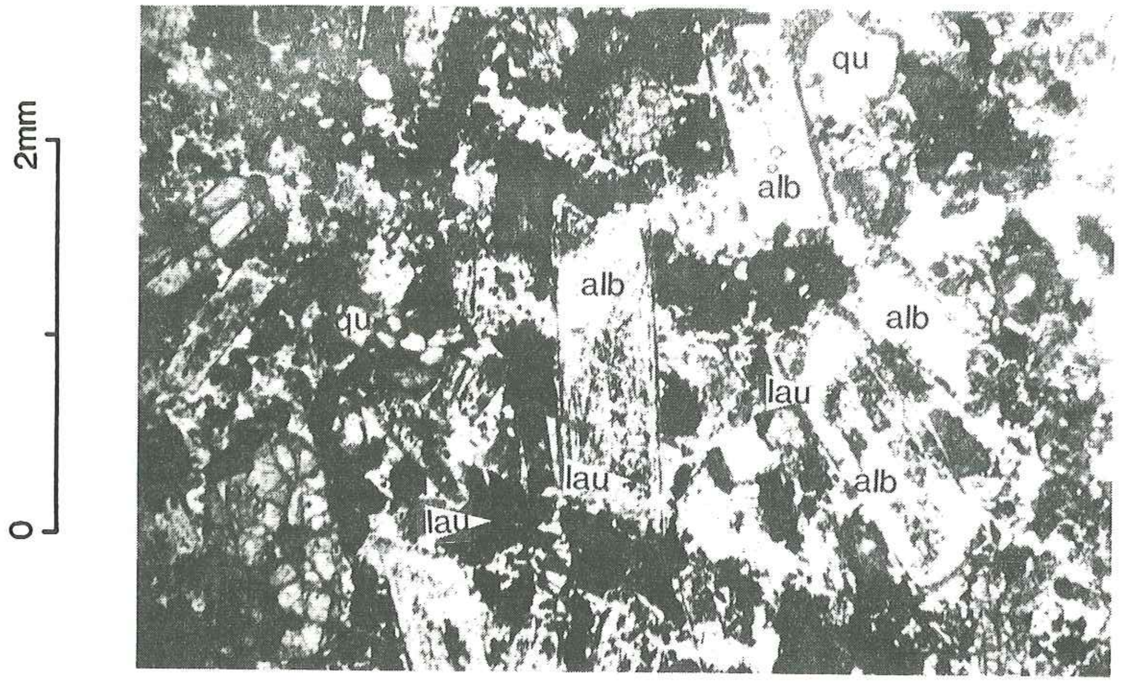


Fig. 22. Photomicrograph of mottled sandstone between parallel polars. The specimen was "stained" with oxalic acid for laumontite which, by the oxalate deposit, is rendered opaque in ordinary, plane-polarized light (most dark areas in photomicrograph). Staining shows that laumontite occurs as replacement of the interstitial matrix between framework grains, and that it forms irregular deposits on and linings around plagioclase grains.

study was kept moist by occasionally immersing it in distilled water during the examination, and usually a second, untreated thin section was prepared from the same specimen for comparison.

6.2.1.2. *Occurrence of laumontite*

Staining shows that laumontite extensively replaces plagioclase and occurs as interstitial cement, where it possibly formed as an alteration product of argillaceous material. The assumption that laumontite may replace the original glassy matrix of andesite clasts (Martini and Vuagnat, 1970) could not be confirmed with certainty by the new staining technique; it mainly alters to chlorite and sphene.

Replacement of plagioclase by laumontite is often wholesale; where incomplete, there is optical continuity between the two minerals, or nearly so. Partial replacement may be preferential of either the outer margin or interior core; ocassionally it is indiscriminantly patchy throughout. As a cement-forming mineral, it frequently occurs as granular or bladed masses, often radially disposed. Where

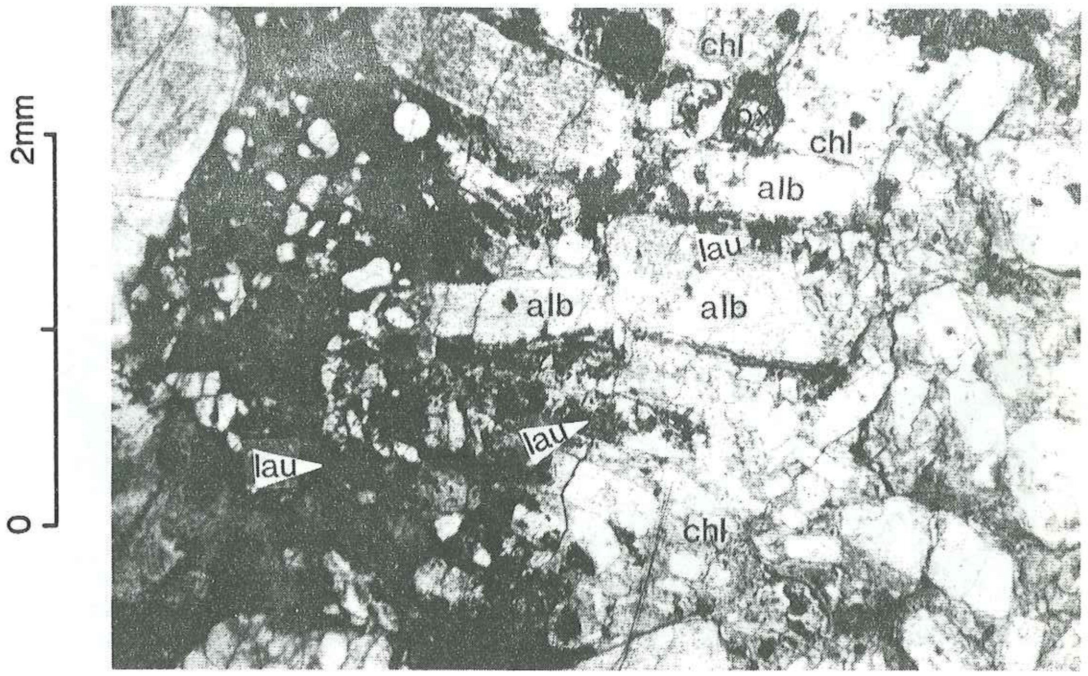


Fig. 23. Photomicrograph of boundary between andesite cobble (right) and fine-grained interstice (left); after laumontite staining; in ordinary, plane-polarized light. As in the previous photomicrograph, laumontite thoroughly replaces the sedimentary matrix between detrital grains (left). Laumontite locally extends 1 mm beyond margin of cobble (towards the right), as linings around (mostly above) or deposits on (mostly below) plagioclase.

larger masses engulf sizeable portions of rock, clasts of pyroxene and amphibole remain largely unaffected, apart from occassional fillings in fractures and linings around grains. It is interesting that, frequently, the majority of albite fragments that are firmly embedded in a laumontite groundmass have largely remained intact (fig. 22). This may be taken as an indication that laumontite initially invaded the fine-grained sedimentary matrix through the agency of solutions prior to its partial penetration into framework clasts, perhaps drawing some of the required lime from the surrounding plagioclase grains. This is substantiated by the common deficiency of laumontite within larger andesite clasts, suggesting that permeability was a major factor during laumontitization. Where laumontite does invade an andesitic pebble, it replaces only plagioclase, beginning at the pebble margin and proceeding inward. The outer laumontized margin may be of variable width or missing, altogether, indicating various stages of progressive infiltration of laumontite-forming solutions into the clasts (fig. 23). Consequently, the extent to which laumontitization takes place may partly depend on the size of the clasts and, therefore, the grain size of the sedimentary rock. In view of the fact that laumontite is generally absent within altered clasts of andesite in the **Briones**

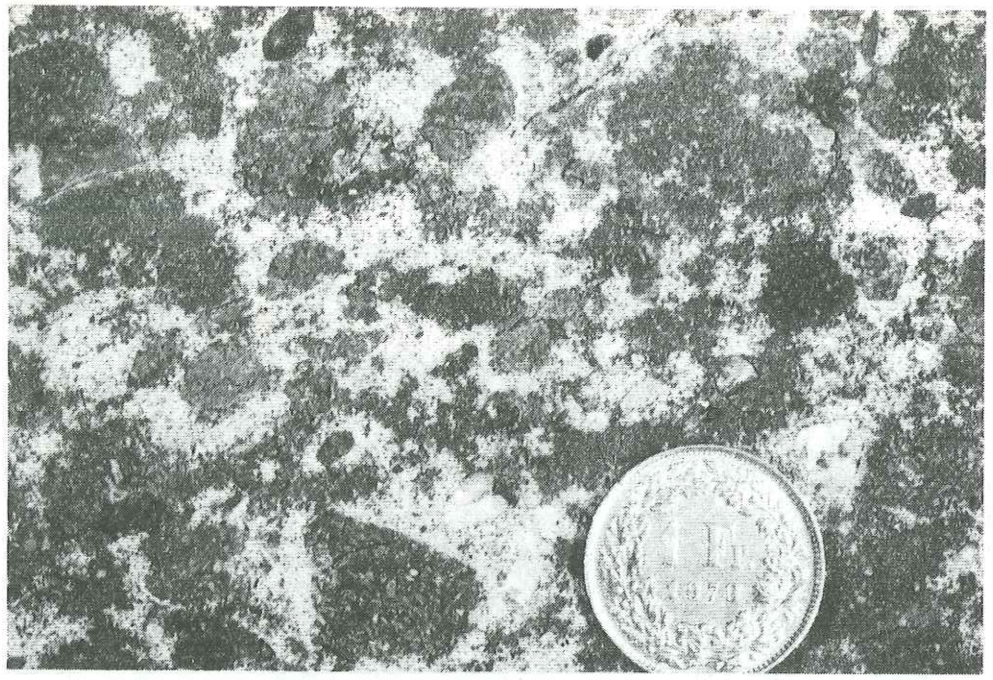


Fig. 24. Photograph of polished slab of rock taken from basal coarse-grained portion of mottled turbidite. Whereas most dark areas are andesite clasts, the lighter-colored areas comprise interstitial aggregates of laumontite. Note sharp outline of andesite pebble immediately to the left of coin, and of those in upper-left corner of photograph. The outlines of most other pebbles, however, are less distinct.

Sandstone (Madsen and Murata, 1970), a laumontized sedimentary rock of lower metamorphic grade, it is possible that the penetration of clasts will gradually take place and progress with increasing grade.

The distribution of laumontite within a given sandstone body - both as a cement-forming mineral and replacement of plagioclase - is thus mainly governed by grain size, since this property largely determines the permeability and amount of potentially reactive interstitial clay minerals in a sedimentary rock. In that most turbidite beds of the Champsaur Sandstone are graded, there is a progressive change in the amount of fine-grained material and, therefore, laumontite from the base of the bed towards the top; furthermore, within each layer, laumontite is often found concentrated in the interstitial matrix. The result is that the distribution of laumontite is very irregular within a graded turbidite bed. This is easily seen in the field by the distinctive mottled appearance laumontite usually produces in these rocks. The basal, coarse-grained portion of the graded bed is characterized by large, indistinct, irregularly patchy, lighter- and darker-colored domains (fig. 24). The darker areas are commonly occupied by andesite pebbles in which chlorite is the dominant secondary mineral, having totally replaced the original glassy groundmass; due to the progressive laumontitization of plagioclase phenocrysts around the rims, the outlines of these pebbles often appear indistinct. The lighter-colored areas comprise finer-grained, interstitial matrix in which laumontite pervades the rock. With decreasing grain size towards the top of the bed, a point is reached where larger fragments no longer interrupt the pattern, and differences in grain size between the framework grains and intergranular matrix become less distinct; well defined circular accumulations of laumontite gradually begin to emerge, cementing the grains within a radius of a few milimeters. The aggregates may assume an orderly arrangement which was found to be favored in grain sizes ranging from 0.2 to 1.0 mm in both the Champsaur and **Briones Sandstones** (fig. 25). It is not clear why the spots should be so well defined and regularly spaced throughout the rock, though grain size is obviously a factor. If unrelated to porosity and permeability, then perhaps it may have something to do with the nature and amount of argillaceous components. Laumontite might have formed as an alteration product of a clay mineral (see below) and nucleated in interstices containing an appreciable amount of this potentially reactive material. The nucleation sites are more closely spaced towards the top of the bed, in a direction where we would expect the clay-mineral content to increase; the spots gradually begin to coalesce until they are finally merged, giving rise to a whitish, fine-grained rock rich in laumontite. Where the upper portion of the turbidite bed is laminated, the highest zone is characterized by regular alternations of light and dark laminae, presumably reflecting differences in clay-mineral content and permeability. Note that the appearance of the Champsaur Sandstone closely matches the field description of laumontitized sedimentary rocks given by Hoare et al. (1964, p.C76) in Alaska, in which separate beds of diverse grain size display the same variety of structures that is developed vertically in a single, graded turbidite of the Champsaur. The fact that the ovoids may be oriented with their long dimension parallel to the bedding seems to indicate that, once nucleated in an anisotropic hydrologic environment, the transfer of components and subsequent growth of laumontite will be favored in directions of greater permeability.

6.2.1.3. Origin of laumontite

Laumontite occurs as replacement of plagioclase and as interstitial cement. The following reactions have been proposed for replacement of calcic plagioclase by laumontite:

$$(1)\quad \underset{\text{anorthite}}{0.99CaAl_2Si_2O_8} + \underset{\text{water}}{1.95H_2O} \dashrightarrow \underset{\text{laumontite}}{0.49CaAl_2Si_4O_{12}\cdot 4H_2O} + \overset{\text{materials}}{0.50CaO} +$$

$$\underset{\text{removed in solution}}{0.50Al_2O_3 + 0.02SiO_2}\ \text{(Coombs, 1954); and}$$

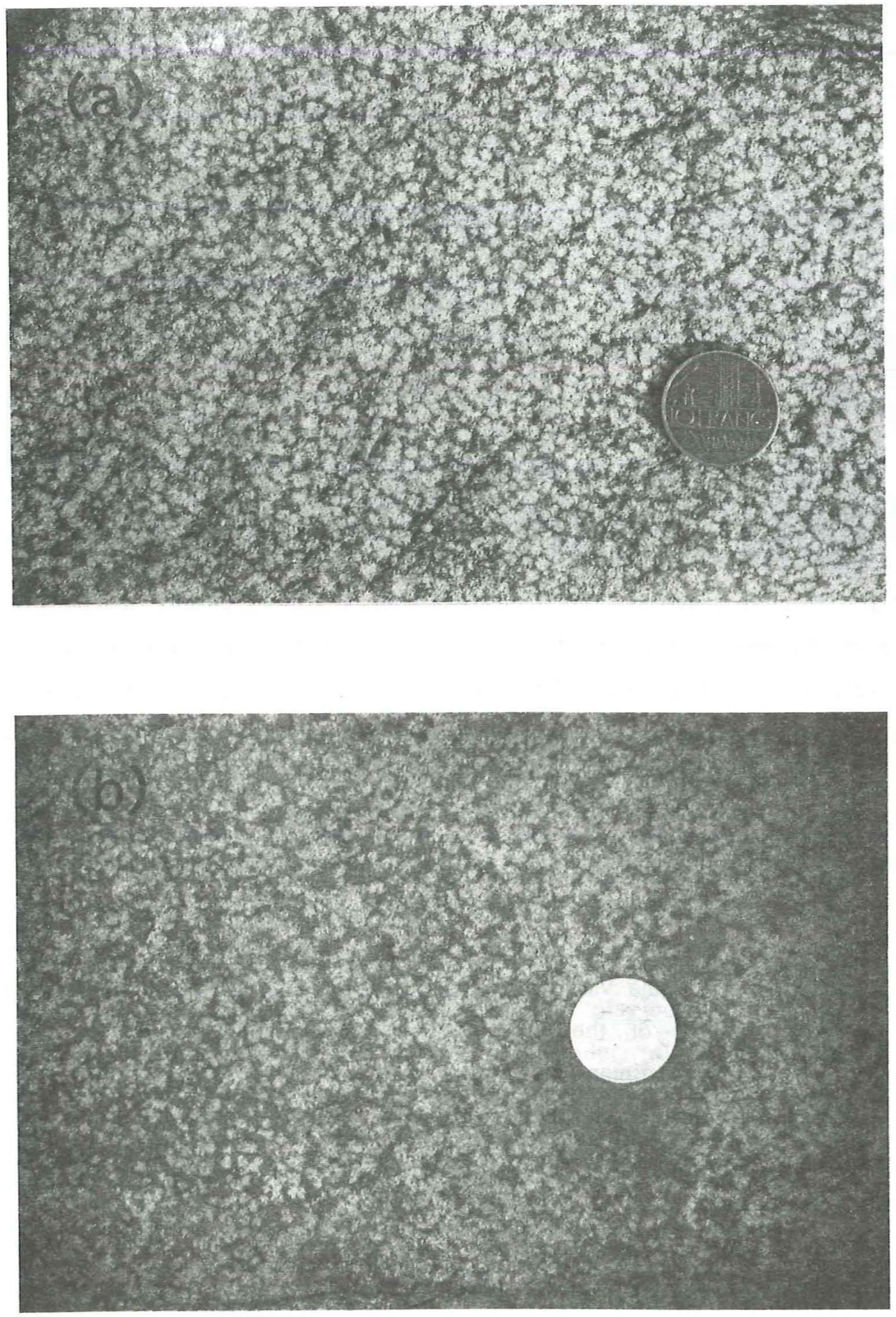


Fig. 25. Well defined, regularly spaced, circular aggregates of laumontite cement in fine-grained layers of Champsaur (a) and Briones (b) Sandstones (approximately the same scale).

$$(2)\ \overset{\text{labradorite}}{NaAlSi_3O_8CaAl_2Si_2O_8} + \overset{\text{quartz}}{2SiO_2} + \overset{\text{water}}{4H_2O} \text{--->} \overset{\text{laumontite}}{Ca(AlSi_2O_6)_2.4H_2O} + \overset{\text{albite}}{NaAlSi_3O_8}$$

(Martini, 1968)

These reactions imply that laumontitization might be associated with albitization of calcic plagioclase, which is certainly valid in laumontized rocks of lower grade, where laumontite is virtually absent in strata retaining unaltered plagioclase (Madsen and Murata, 1970), or where plagioclase is less calcic in rocks containing appreciable amounts of laumontite (Hoare et al., 1964). However, the silica which would be produced by the first reaction would have to be carried away in solution, as no secondary quartz was detected in the Champsaur samples, apart from in fracture fillings and one crystal which was stumbled upon in an andesite cobble (see table III). Furthermore, the silica required by the second reaction cannot have been derived from quartz because the invariably sharp outlines of quartz fragments demonstrate that this mineral was chemically inert in highly laumontized zones.

Accumulations of laumontite in fine-grained layers and interstices suggest that it might also have formed at the expense of argillaceous material. The following laumontite-producing reactions have been put forward that require clay minerals:

$$(3)\overset{\text{calcite}}{CaCO_3} + \overset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4} + \overset{\text{quartz}}{2SiO_2} + \overset{\text{water}}{H_2O} \text{--->} \overset{\text{laumontite}}{CaAl_2Si_4O_{12}.4H_2O} + CO_2$$

(Zen, 1961);

$$(4)\ 13.5[\overset{\text{montmorillonite}}{Ca_{0.33}(Al_{3.34}Mg_{0.66})Si_8O_{20}(OH_4)}] + \overset{\text{calcite}}{15CaCo_3} + \overset{\text{water}}{59H_2O} \text{--->}$$

$$\overset{\text{chlorite}}{[(Al_3Mg_9)(Al_3Si_5)O_{20}(OH)_{16}]} + 19.5[\overset{\text{laumontite}}{CaAl_2Si_4O_{12}.4H_2O}] + \overset{\text{quartz}}{25SiO_2} + 15CO_2$$

(Madsen and Murata, 1970)

In an attempt to uncover the precursor clay mineral, all sandstone units were sampled and analyzed for their clay-mineral contents by x-ray analysis of oriented powders, including the more internal units that contain appreciable amounts of andesite, but no laumontite (section 6.5). Unfortunately, chlorite and illite are the only clay minerals that were detected by this method in all the units. It is nevertheless possible that, with rising temperature and pressure, remainders of the original reactive clay mineral - presumably a montmorillonite - were entirely decomposed. This seems likely considering that relict montmorillonite (smectite) was detected by Sawatzki (1975, p. 340) in rocks of lower rank, more specifically, in graywackes that are transitional between the zones characterized by heulandite and laumontite. For instance, in the Niigata oil field, Japan, montmorillonite progressivley gives way to corrensite or a swelling chlorite, then to chlorite (Iijima and Utada, 1971; see also Sawatzki, 1975, and Kübler 1973a, 1973b).

6.2.2. Albite

As already noted in section 3.2.1., the original plagioclase has been extensively replaced by crystallographically low-temperature albite. Initially, the plagioclase was more calcic, usually in the compositional range of labradorite and, in extreme case, bytownite (Martini, 1968). The original, more basic plagioclase is occasionally found in some strongly calcitized zones, such as bed margins and diagenetic concretions, where calcite functioned as a sealant against reactive solutions. Where present, primary, more calcic plagioclase is easily recognized by its conspicuous compositional zoning and clear, translucent appearance, which is in marked contrast to the customary, uniformly turbid nature in the altered state. On rare occasions, replacement may be progressive and preferential, leading to the presence of more than one plagioclase in the same rock. In the Taveyanne Sandstone, albitization is considered to have commenced at low temperature, becoming progressively more thorough with increasing grade (Stalder, 1979); the original calcic plagioclase may disappear altogether in the highest grades (Vuagnat, pers. comm.). In the Champsaur, the primary plagioclase has been largely obliterated, even in strongly calcitized zones. Locally, it may nevertheless persist, and its preservation may sometimes be favored in cobbles which functioned as an additional sealant (table III). By contrast, the original plagioclase was found to be still largely preserved in calcitic concretions of the **Briones Sandstone**, which is in agreement with the notion that albitization is less developed in rocks of lower metamorphic grade.

As outlined above, it appears that albitization might be closely linked with the formation of laumontite, either by direct replacement through reactions (1) and (2), or by metasomatism between the sedimentary matrix and individual plagioclase grains. Following wholesale replacement of calcic plagioclase by laumontite, albite may also have been produced through subsequent replacement of laumontite pseudomorphs by prehnite (section 6.2.5.).

6.2.3. Chlorite

In the Champsaur, two contrasting varieties of chlorite may be distinguished on the basis of optical properties. The first kind is extremely lamellar, deeply colored in shades of brown, and strongly birefringent, its interference colors reaching first-order red or even second-order blue. Surprisingly, qualitative microprobe analyses show that this chlorite is strongly depleted in iron. The second type is generally light-green and much less birefringent, sometimes nearly isotropic, especially within andesite grains. This chlorite, by contrast, contains substantial amounts of both iron and magnesium. Though both varieties of chlorite may often be present in a given sandstone specimen, there is a strong positive correlation between the dark-colored, strongly birefringent variety and laumontite, pumpellyite and prehnite. Therefore, whereas this type is diagnostic of the mottled zeolite facies, the other, light-green variety is characteristic of the "vert facies".

The distribution of chlorite is easily seen in the field by the dark color it produces in the mottled rocks. It is the most prominent secondary mineral in andesite fragments, in the interstitial matrix between lighter-colored laumontite spots, and in the upper, dark-colored, parallel-bedded laminae. In that chlorite pervasively penetrates andesite cobbles, its distribution is more or less uniform throughout the rock, anywhere aside from strongly laumontitized parts. However, local concentrations of chlorite in dark, anastomosing bands that cut across apparently solid rock (fig. 27) indicate the presence of a second generation in which permeability played a major role.

In thin section, chlorite occurs as an alteration product of volcanic glass, as cement, and as replacement of ferromagnesian minerals and plagioclase. Replacement of pyroxene by chlorite may develope progressively from cleavage traces and proceed inward until the entire crystal is consumed. There are indications that chlorite may also replace other constituents, even quartz, though it is more likey that such modes of occurrence represent fracture fillings and linings of cement in and around detrital grains. The exact nature of the apparent pseudomorphs is mostly unclear, apart from those that have assumed the typical euhedral outlines of plagioclase phenocrysts. Chloritization of the intergranular sedimentary matrix has generally proceeded to completion, apparently misleading some authors, those who believe to have perceived a massive or tuffaceous volcanic rock rich in interstitial volcanic glass (Termier and Lory, 1895; Bellair, 1957; Beuf et al., 1961; Giraud, 1983). Wholesale replacement of the argillaceous matrix may have taken place by a process similar to reaction (4), which requires a clay mineral and produces both chlorite and laumontite, and in the **Briones Sandstone** it is possible that both of these minerals were formed by a single event (Madsen and Murata, 1970). As an alteration product of volcanic glass, chlorite pervades the groundmass of andesite fragments and occurs in former glass inclusions of plagioclase phenocrysts. Chloritization, both as cement and replacement of volcanic glass, has generally liberated sphene.

6.2.4. Pumpellyite

Due to the variable amounts of iron it may contain, the appearance of pumpellyite may be anywhere between colorless and dark-green in ordinary plane-polarized light. Most commonly, it occurs as small, nearly equidimensional grains, either scattered or in granular aggregates. Grain size is variable, ranging from dense, microcrystalline masses to well developed individual larger grains. Sheaf-like laths may occur in clusters and assume a radial or subparallel arrangement.

First and foremost, pumpellyite preferentially occurs within the outlines of plagioclase grains. Since replacement of plagioclase by laumontite is optically continuous, it is mostly unclear whether pumpellyite is replacing laumontite or the plagioclase itself. Laumontite staining confirms that pumpellyite does occur within those portions of plagioclase that are devoid of laumontite, so there is little doubt that pumpellyite may be associated with albite, presumably as replacement of calcic plagioclase (see below). On the other hand, it is more difficult to use the staining technique to establish a direct relationship between laumontite and pumpellyite because the oxalate deposit can evidently conceal fine-grained aggregates of pumpellyite. However, judging by the difference in the amount of pumpellyite seen in both a treated and untreated thin section, it follows that some of the pumpellyite ocurring within the outlines of plagioclase grains must have replaced laumontite. Pumpellyite also occurs as a widespread alteration product of laumontite and chlorite in the interstitial cement. Here, laumontite is more easily identifiable by conventional microscopic methods on account of its characteristic habit in masses of interlocking radial aggregates, and its replacement by pumpellyite is therefore more apparent. Pumpellyite may also form a microcrystalline or finely granular deposit in the chloritic groundmass of andesite fragments, where the latter has replaced the original volcanic glass. Immediately adjacent to veins, the entire rock is charged with dense replacement masses of pumpellyite, often thoroughly consuming all of its constituents other than quartz (fig. 26).

In summary, within the ordinary graywacke, pumpellyite primarily occurs as an alteration product of laumontite, chlorite, and plagioclase, all of which comprise

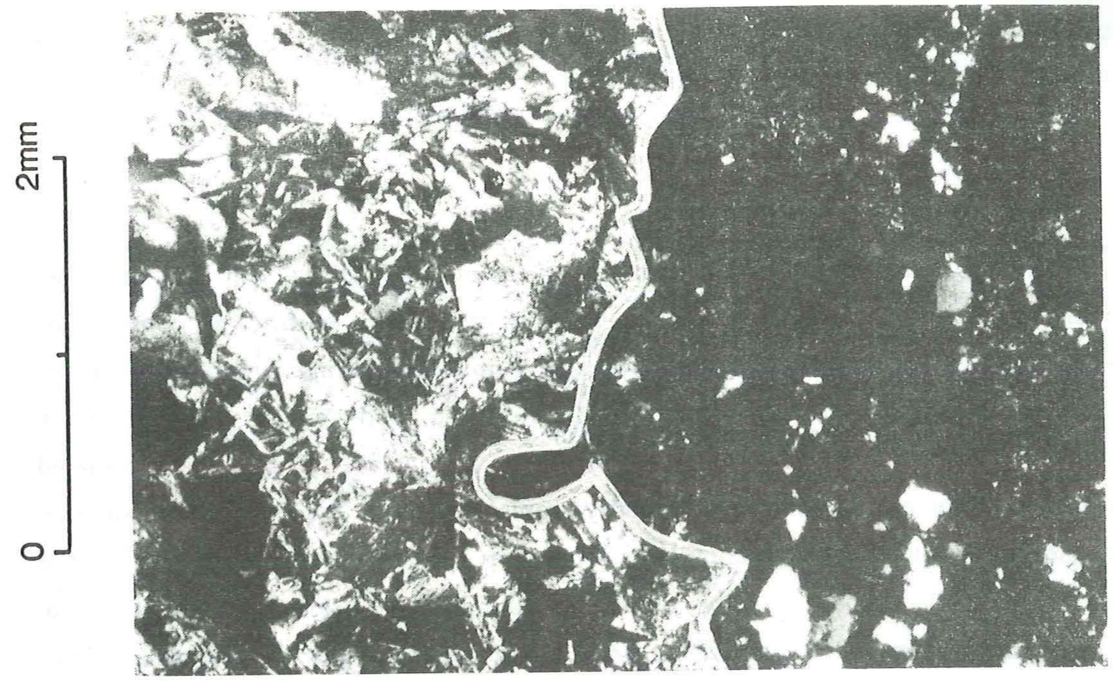


Fig. 26. Photomicrograph (polars crossed) of sharp contact between hydrothermal vein (left) and adjacent host rock (right). The contact is highlighted by white line. The fissure is filled exclusively by interlocking, fan-shaped, radial and lamellar masses of prehnite which, in this case, does not penetrate the neighboring rock. Pumpellyite (right), by contrast, forms a dense, microcrystalline replacement mass in which individual clasts of quartz and quartzite persist.

potential reactants that are required for the formation of pumpellyite (Bussy and Epard, 1984):

(5) 31 laumontite + 25 calcite + 2 chlorite ---> 14 pumpellyite + 48 quartz + 87 H_2O + 25 CO_2

(6) 31 labradorite + 25 calcite + 2 chlorite + 14 quartz + 37 H_2O ---> 31 albite + 14 pumpellyite + 25 CO_2

Pumpellyite apparently does not occur in veins but may extensively replace the adjacent host rock. Furthermore, replacement by pumpellyite may at times preferentially occur in linear concentrations that cut across the sedimentary rock. On the other hand, pumpellyite may, in some cases, be subdued or partially excluded from larger andesite cobbles which may have obstructed the infiltration of pumpellyite-producing solutions. This suggests that, although pumpellyite apparently cannot crystallize directly from an aqueous solution under these metamorphic conditions, its formation is to some extent dependant on reactions between the rock and interstitial fluids.

6.2.5. Prehnite

Prehnite is far less abundant than either laumontite, albite, chlorite, or even pumpellyite. In the average thin section, it primarily occurs within the confines of plagioclase or in the cement. In both cases, it commonly forms irregular, anhedral replacement aggregates that are often radially disposed, and generally appears dirty in ordinary, transmitted, plane-polarized light. In plagioclase, it may be associated with either albite or laumontite; frequently, replacement of the original plagioclase or laumontite pseudomorph is complete. Where prehnite occurs sporadically in the cement, it mostly appears to be replacing laumontite. Prehnite also forms a prominent constituent of hydrothermal veins, in association with quartz and calcite (fig. 26). Here, by contrast, it is characterized by transparent, euhedral crystals occurring in fan-shaped lamellar masses. In general, it fully penetrates the adjacent host rock within a few millimeters, forming a regular and thorough replacement mosaic produced by interlocking radial crystals of prismatic or fibrous habit. In these reaction zones, aggregates of prehnite suppress or replace masses of pumpellyite, indicating that its formation presumably occurred subsequent to that of pumpellyite.

However, apart from in veins and the adjacent reaction zones, prehnite is sparse and its occurrence is confined to replacement of plagioclase and laumontite within the ordinary rock. The following reactions are relevant (Martini, 1968):

(7) $$2[\overset{\text{labradorite}}{NaAlSi_3O_8.Ca(Al_2Si_2O_8)}] + 0.33K_2O + \overset{\text{quartz}}{SiO_2} + \overset{\text{water}}{0.66\ H_2O} \dashrightarrow$$

$$\overset{\text{prehnite}}{Ca_2Al_2(OH)_2Si_3O_{10}} + \overset{\text{muscovite}}{0.66KAl_2(OH)_2AlSi_3O_{10}} + \overset{\text{albite}}{2NaAlSi_3O_8}$$

(8) $$\overset{\text{labradorite}}{NaAlSi_3O_8.CaAl_2Si_2O_8} + \overset{\text{calcite}}{CaCO_3} + \overset{\text{quartz}}{SiO_2} + \overset{\text{water}}{H_2O} \dashrightarrow$$

$$\overset{\text{prehnite}}{CaAl_2(OH)_2Si_3O_{10}} + \overset{\text{albite}}{NaAlSi_3O_8} + \overset{\text{carbon dioxide}}{CO_2}$$

(9) $$\overset{\text{laumontite}}{2Ca(AlSi_2O_6)_2.4H_2O} + 0.33K_2O \dashrightarrow \overset{\text{prehnite}}{Ca_2Al_2(OH)_2Si_3O_{10}} +$$

$$\overset{\text{muscovite}}{0.66KAl_2(OH)_2AlSi_3O_{10}} + \overset{\text{quartz}}{3SiO_2} + \overset{\text{water}}{2.33H_2O}$$

(10) $$\overset{\text{laumontite}}{Ca(AlSi_2O_6)_2.4H_2O} + \overset{\text{calcite}}{CaCO_3} \dashrightarrow \overset{\text{prehnite}}{Ca_2Al_2(OH)_2Si_3O_{10}} +$$

$$\overset{\text{quartz}}{SiO_2} + \overset{\text{water}}{3H_2O} + \overset{\text{carbon dioxide}}{CO_2}$$

It is uncertain whether reactions (7) and (8) could have taken place as such, since they would require substantial amounts of quartz, an apparently unreactive mineral which is persistent even in the midst of extensive replacement aggregates adjacent to veins. By contrast, the silica that would have been produced by reactions (9) an (10) must have been removed in solution and might have recrystallized in fractures as quartz.

6.2.6. Sphene

Sphene invariably forms a prominent secondary constituent in both the "vert" and zeolite-facies assemblages. It occurs either as scattered grains or in granular clusters, chiefly within the confines of the interstitial cement and in the groundmass of andesites. Sphene is commonly closely associated with chlorite, and it is therefore assumed that it formed as a by-product in the alteration of the sedimentary matrix and original volcanic glass to chlorite, but apparently less so or not at all during chloritization of plagioclase and augite.

6.2.7. Sericite

In the mottled facies, plagioclase is frequently stippled with minor, almost negligible quantities of minute micaceous flakes. The white mica was not determined by the author and is loosely referred to as sericite, though it may actually be paragonite (Martini, 1968; Sawatzki, 1975). The degree of sericitization may rise to substantial proportions in the "vert facies", where sericite occurs increasingly in the cement, though here it is difficult to distinguish it from calcite. In rare, compositionally zoned plagioclase crystals, it is often the calcic core that has preferentially been altered to sericite. Throughout the Champsaur, there is a crude, positive correlation between the amounts of sericite and calcite, both of which formed in part by conversion of calcic plagioclase to albite (section 6.3.3.).

6.2.8. Hydrothermal Veins

Massive, amalgated sandstone bodies occurring in the mottled facies are frequently crossed by white hydrothermal veins which are commonly fringed by dark-green replacement masses in the host rock (fig.26). Whereas in the fractures prehnite constitutes the mineral filling, often in association with calcite and quartz, the adjacent rock is charged with aggregates of both prehnite and pumpellyite, rarely with minor replacement aggregates of epidote. Since replacement is often indiscriminate and thorough, sedimentary textures are commonly less apparent within these margins of altered rock. Replacement masses of pumpellyite generally predate and may extend a few millimeters beyond the range of prehnite into the adjacent rock. The latter invariably lines the fracture adjacent to its replacement front, the remaining space of the fracture often being filled by quartz and calcite. The crystallization sequence in and adjacent to fracture fillings is therefore inferred to have been pumpellyite, prehnite, then either quartz or calcite. This is superimposed on and therefore postdates the formation of albite, laumontite, and chlorite within the country rock.

The sequential and spatial relationships are similar to those observed in the Taveyanne Sandstone, where assemblages also deviate to higher metamorphic grades in the vicinity of fissures (Martini, 1968; Sawatzki, 1975; Bussy and Epard, 1984). In the laumontite-bearing rocks, laumontite has similarly been replaced by pumpellyite and prehnite, or epidote, and these deviations have been ascribed to local variations in the activity of H_2O by Coombs (1971): whereas interstitial solutions in the country rock would be confined and subjected to lithostatic pressure exerted by thrust loading, it is reasonable to assume that the pressure in open joints was close to hydrostatic and lower than that created within the rock, thus favoring the development of phases less hydrous than laumontite. An additional or alternative factor may have been the uninhibited circulation of hydrothermal fluids that should be guarantied along open fractures and joints. With rising temperature and pressure, the transfer and exchange of essential components are therefore ensured, and the assemblage may easily readjust. At a distance from these fractures, pumpellyite and, especially, prehnite are much less abundant in the Champsaur Sandstone, where the intergranular flow of fluids and transmission of components are inferred to have been more sluggish and metamorphic reactions slow. In a few andesite cobbles, pumpellyite was found to be partially excluded or to occur in smaller amounts. Similarly, prehnite was never detected in larger andesite fragments, though this may not be conclusive because, even in the ordinary sandstone sample, it rarely occurs in substantial amounts. It is nonetheless possible that the development of prehnite and pumpellyite is partly dependent on grain size and, therefore, porosity and permeability of the rock. If so, this may to some extent be due to the lack of laumontite, a potential precursor of both prehnite and pumpellyite.

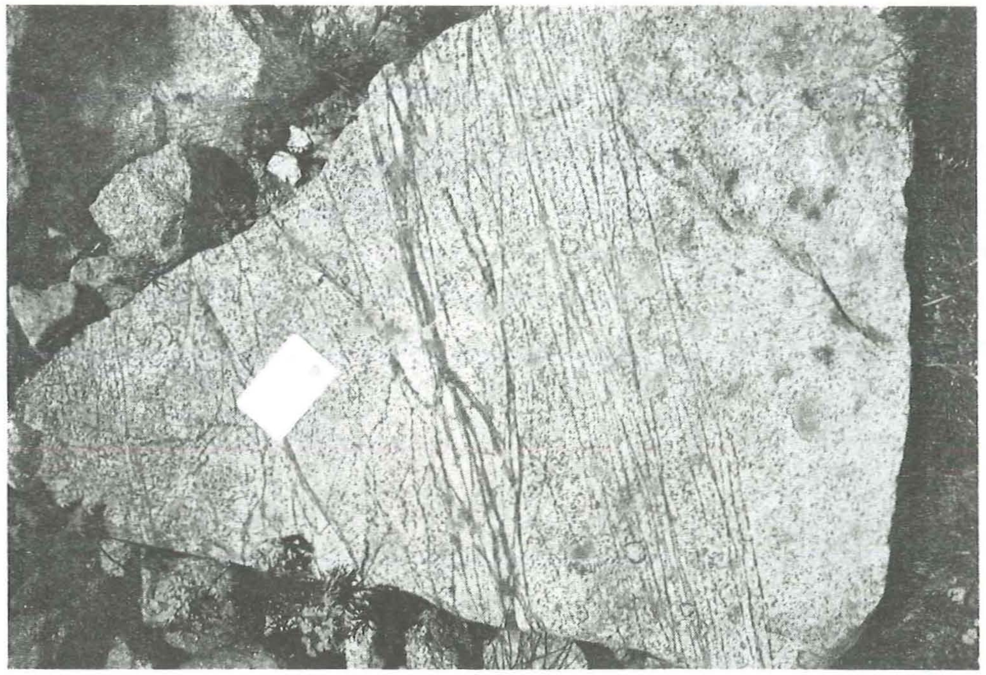


Fig. 27. Dark, anastomosing replacement masses of chlorite superimposed on laumontite mottling in large boulder.

Massive sandstone bodies are occasionally crossed by dark, anastomosing bands that are crudely aligned parallel to the local pattern of veins (fig. 27). These replacement masses occur where reactive solutions were able to diffuse more freely, yet mostly without any apparent openings or displacements in the affected portions of the rock. Most commonly, they delineate higher concentrations of chlorite, basically in the same modes of occurrence as in the ordinary graywacke. Though there are no important variations in optical properties, it is reasonable to assume that there are at least two generations of chlorite, the second of which was superimposed on the mottling and therefore the development of laumontite and albite. On a smaller scale, there may also be similar concentrations of pumpellyite.

6.3. The Vert Facies

The "vert facies" comprises local departures from the characteristic zeolite facies assemblage, in which the disappearance of calc-silicates coincides with the introduction of variable amounts of calcite. The vert facies was first differentiated as a separate metamorphic entity in the Taveyanne Sandstone by Martini (1968), who compared it to the chlorite facies described by Seki (1961) in Japan. Because its widespread occurrence is not associated with a specific zeolite- or prehnite-pumpellyite assemblage in the external Alps, it does not as such comprise a real metamorphic facies and is therefore commonly referred to in quotation marks. In order to denote the appearance of a freshly broken rock surface, Martini (1968) coined the descriptive term "vert", which is merely the French word for "green". The rock may, however weather to shades of brown, often with the development of an orange hue which is most apparent in sandstone bodies that are unrelated to shale, i.e. in the vicinity of limestones and faults.

6.3.1. Occurrence and Origin

The "vert facies" occurs in the same sandstone units in which the zeolite facies may be developed. Within the area delineated by the strata of appropriate bulk composition (section 6.1.2.), the vert facies is confined to:

1) thin sandstone beds intercalated in major shale sequences;
2) the upper and lower calcitized margins of thick sandstone beds adjacent to shale breaks;
3) in diagenetic concretions cemented by calcite, which often surround rip-up clasts of shale (see Vuagnat, 1949);
4) locally, in sandstone bodies overlying nummulitic limestones (see fig. 3);
5) locally, in the vicinity of major faults (see fig. 3).

In almost all of these occurrences, the vert facies is closely associated with either limestone or shale containing variable amounts of calcite. There is therefore little doubt that the distribution of the vert facies is governed by the immediate availability of lime and CO_2 which apparently can migrate into the adjacent rock to form calcite. The possibilty that the development of the "vert facies" could be favored in rock bodies subjected to higher tectonic pressures (Martini, 1968) may essentially be ruled out, even in the vicinity of faults. A more reasonable assumption is that solutions were able to circulate more freely along local fractures and faults, impregnating the adjacent bodies of rock with calcite. The antipathetic relationship between calcite and calc-silicates, notably laumontite, is common in incipiently metamorphosed sandstones, either because early, interstitial precipitation of calcite inhibits the transmission of aqueous solutions (Martini and Vuagnat, 1967; Madsen and Murata, 1970; Sawatzki, 1975; Stalder, 1979) or because the

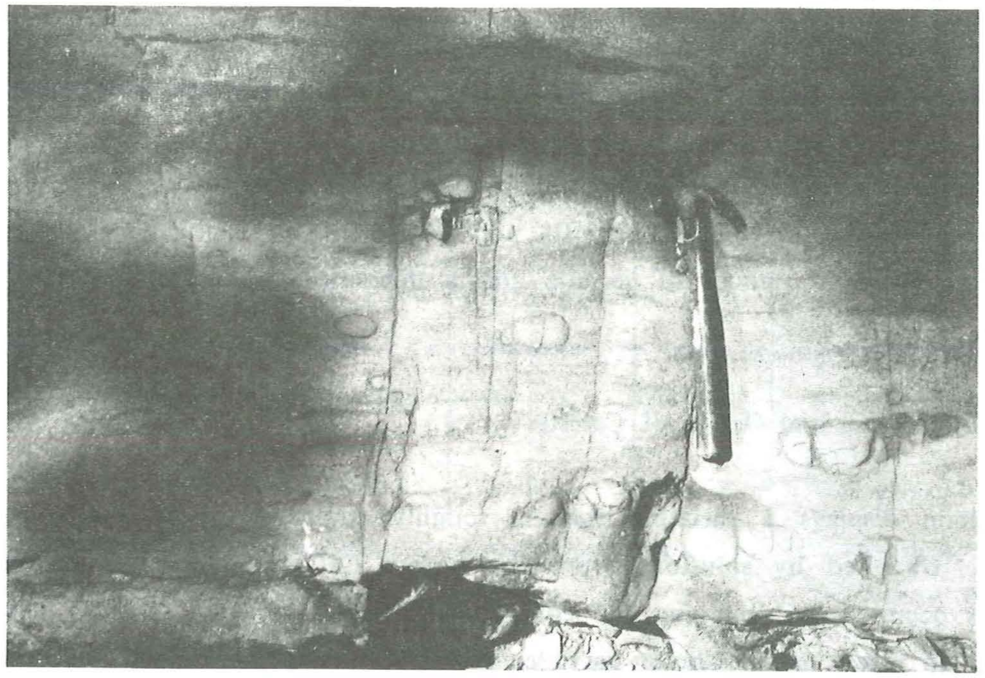


Fig. 28. Diagenetic concretionary nodules (below and to the left of hammer) in vaguely mottled Briones Sandstone, Penitencia Creek, Alum Rock Park, Santa Clara County, California.

associated rise in the activity of CO_2 significantly reduces the stability of zeolite facies assemblages (Coombs, 1971).

The vert facies was also found in the **Briones Sandstone**, in diagenetic concretions in which the original, compositionally zoned calcic plagioclase is preserved (fig. 28). The impregnated rock lacks laumontite, and the framework grains are tightly cemented with calcite. The absence of calcitized bed margins in the area studied is presumably due to the lack of significant shale partings along Penitencia Creek.

6.3.2. The Characteristic Assemblage

The "vert" facies was originally intended to denote individual sandstone beds or larger bodies of strata that are characterized by the assemblage albite, chlorite, sericite, and sphene, in addition to prehnite which may be more or less abundant; calcite was mentioned in passing to occur in some specimens and was not regarded as diagnostic (Martini, 1968). The "vert" facies is used by the present author to include all five modes of occurrence enumerated above, in which there is usually a total lack of calc-silicates and nearly always variable amounts of calcite. Ideally, it comprises the following assemblage: calcite, chlorite, albite, sphene, and sericite. Calcite and chlorite extensively replace and pseudomorphose the ferromagnesian minerals, especially augite. Calcite additionally replaces plagioclase. The assemblage is consistent between one mode of occurrence and another, but there are significant differences in the amount of individual constituents, largely as a function of calcite (see tables VII, VIII, and IX). A rise in calcite generally entails an increase in the amount of sericite and a decrease in chlorite and associated sphene.

6.3.3. Disposition and Origin of Calcite

Calcite displays a variation that is roughly compatible with the estimated distance travelled by solutions from the parent CaO-rich rocks. The highest amounts occur in bed margins and concretions situated adjacent to shale partings and rip-up clasts. Here, calcite pervades the sedimentary matrix, replaces detrital minerals, and may partially enter andesite clasts, suppressing chlorite which is largely confined to andesite fragments, as replacement of the groundmass and phenocrysts. Where calcite has penetrated entire sandstone beds intercalated in shale, it is more restrained, and chlorite is no longer restricted to andesite clasts. The least amounts of calcite occur in massive sandstone sequences that display no apparent relationship to marls or shale, where it was introduced from external sources by metasomatism through larger bodies of strata. This is illustrated in the vicinity of faults situated to the east of the Pic du Tourond and, locally, where the Champsaur Sandstone is transgressive onto nummulitic limestones, such as south of the Vieux Chaillol. Though these rocks may contain appreciable amounts of calcite, the quantities are modest in most; calcite, in fact, may not be discernible at all in some thin sections. It is amazing how an environment only slightly enriched in CO_2 may drastically suppress laumontite, pumpellyite, and prehnite.

Stalder (1979) has recognized at least two generations of calcite, the first of which sealed the sedimentary rock and prevented further alteration, the second of which formed as an alteration product of the detrital components and chloritic cement. This is substantiated by field observations disclosing the presence of well defined calcitized bed margins in sandstone beds that are characterized by the same vert assemblage, but with less amounts of calcite than in its edges bordering the shale (Sawatzki, 1975, fig. 11). The calcite occurring in bed margins and concretionary nodules is inferred to have been the first secondary mineral to have formed in the Champsaur Sandstone, by diagenetic precipitation from aqueous solutions in the pores of a largely unconsolidated sedimentary rock. With the

Table VII. Vert assemblages of sandstone beds intercalated in marl.

sample	Calcite	Pyroxene	Chlorite	Amphibole	Sphene	Prehnite	Pumpellyite	Sericite	Laumontite	zoned Plg
9	X	---	X	---	X	---	---	X	---	---
13	X	---	X	---	X	---	---	X	---	---
18	X	(X)	X	---	X	---	---	(X)	---	---
49	X	---	X	---	X	---	---	(X)	---	---
87	X	---	X	---	X	---	---	(X)	---	(X)
92	X	---	X	---	X	---	---	(X)	---	---
93	X	---	X	---	X	---	---	(X)	---	---
108	X	(---)	X	(---)	X	---	---	(X)	---	---
112	X	X	X	X	X	---	?	(X)	X	---
114	X	---	X	---	X	---	---	X	---	---
139	X	---	X	---	X	---	---	X	---	---
140	X	---	X	---	X	---	---	X	---	---
156	X	X	X	---	X	---	---	(X)	---	---
160	X	---	X	---	X	---	---	(---)	---	---
161	X	---	X	---	X	---	---	(---)	---	---

Table VIII. Vert assemblages of sandstone beds with no apparent relationship to marl.

sample	Calcite	Pyroxene	Chlorite	Amphibole	Sphene	Prehnite	Pumpellyite	Sericite	Laumontite	zoned Plg
131	X	---	X	---	X	---	---	(X)	---	---
177	X	---	X	---	X	---	---	(---)	---	---
178	---	---	X	---	X	---	---	---	?	---
223	X	---	X	---	X	?	---	(---)	---	---
227	X	---	(X)	---	X	---	---	(---)	---	---
228	---	X	X	X	X	---	---	X	---	(---)
229	---	---	(---)	---	X	---	---	---	---	---
230	X	---	(X)	---	X	---	---	X	---	---

Table IX. Vert assemblages in calcitic concretions and bed margins.

sample	Calcite	Pyroxene	Chlorite	Amphibole	Sphene	Prehnite	Pumpellyite	Sericite	Laumontite	zoned Plg
14	X	---	X	---	?	---	---	(X)	---	---
17	X	(---)	X	---	X	---	---	X	---	---
22	X	---	X	---	X	---	---	(X)	---	---
34	X	X	X	X	X	---	---	X	---	---
78	X	(X)	X	---	X	---	---	(X)	---	---
163	X	X	X	(---)	X	---	---	X	---	---

--- = none; (---) = negligible; (X) = minor; X = major; ? = doubtful increase in depth of burial by the arrival of rapidly advancing nappes, calcite is believed to have suddenly invaded larger rock masses and to have been activated in the vicinity of limestones and along faults, additionally altering detrital minerals, including andesite clasts. Not all of this lime, however, was derived from an external source; much was presumably liberated *in situ* from calcic plagioclase and clinopyroxene. The formation of late calcite must have occurred prior to that of laumontite, pumpellyite, and prehnite - and therefore, as a by-product, also partly albite - because these minerals are unstable and missing in the presence of any calcite. Considering that the formation of chlorite might have been partly coupled with that of laumontite by reaction (4), which requires calcite, some chlorite in the zeolite facies might have crystallized subsequent to late calcite in the cement. In the vert facies, it is not clear what relation chlorite bears with this calcite. The same holds for albite, where it is not associated with either laumontite, pumpellyite or prehnite, though in all likelihood much of it formed concurrently with late calcite, by albitization of labradorite (Martini, 1968):

$$(11)\ \overset{\text{labradorite}}{3[NaAlSi_3O_8.Ca(Al_2Si_2O_8)]} + K_2O + 2H_2O + 3CO_2 \text{ --->}$$

$$\overset{\text{calcite}}{3CaCO_3} + \overset{\text{muscovite}}{2KAl_2[(OH)_2AlSi_3O_{10}]} + \overset{\text{albite}}{3NaAlSi_3O_8}$$

This reaction is particularly suitable with regard to the frequent synpathetic relationship between calcite and sericite; also, both may form a deposit on albite. On the other hand, it cannot account for the general deficiency of calcite and sericite in strata bordering carbonates and faults, the assemblage of which is dominated by albite and chlorite.

6.4. Sequential Crystallization of Phases

From field and thin-section observations on the mutual relationships between secondary constituents, the following crystallization sequence for the *onset* of individual phases is inferred (cf. Martini, 1968; Sawatzki, 1975; Stalder, 1979):

1) calcite I
2) calcite II, chlorite I, albite
3) chlorite I, albite, laumontite
4) chlorite II
5) pumpellyite
6) prehnite
7) epidote

Whereas sphene invariably formed as a by-product with most chlorite, the beginning of sericitization is thought to have approximately coincided with that of late calcite.

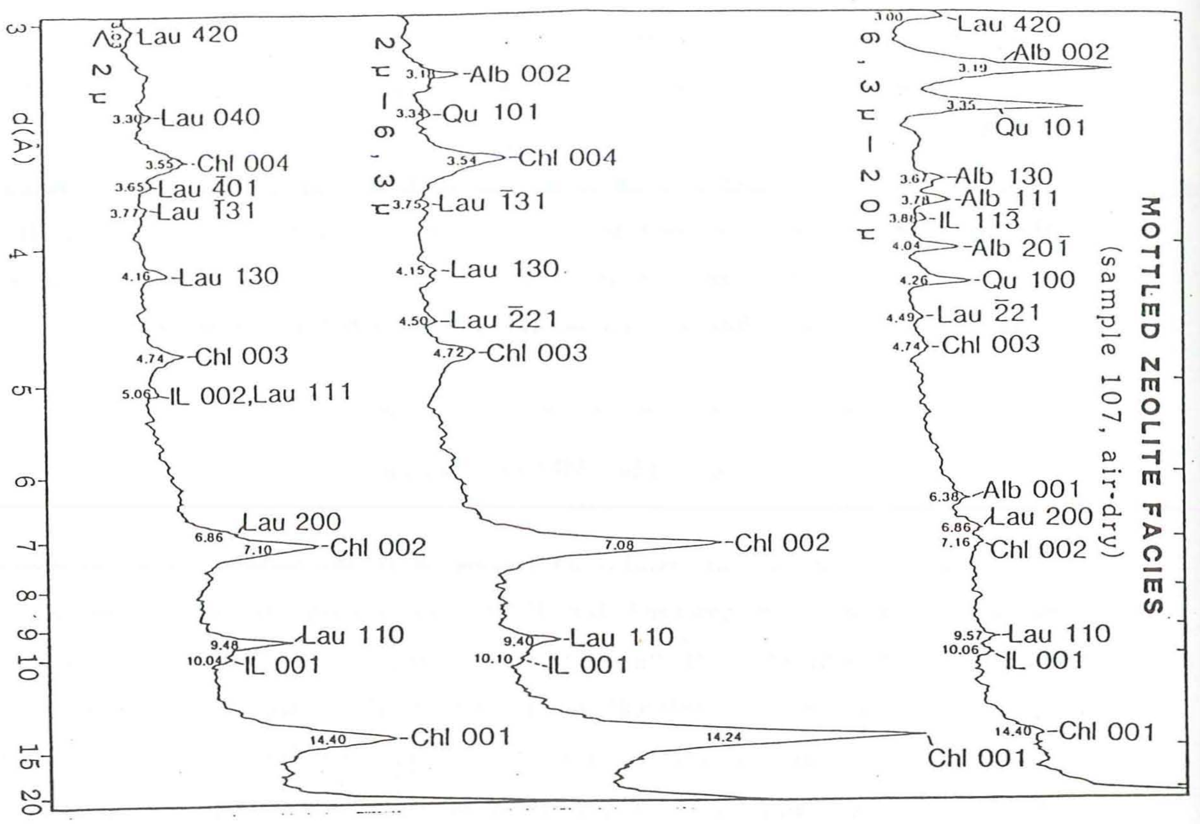
Note that chlorite I and chlorite II do not refer to the chlorites differentiated on the basis of optical properties and composition (section 6.2.3.). Chlorite II is distinguished as "late" chlorite in anastomosing bands that are superimposed on the mottling and, therefore, albite and laumontite (sections 6.2.3. and 6.2.8.).

6.5. Clay Mineral Contents

In the autochthonous unit, sandstones belonging to the vert and mottled zeolite facies were sampled and analyzed for their clay-mineral contents. Among the various modes of occurrence of the "vert facies" (section 6.3.1.), the sampling was confined to sandstone beds intercalated in major shale sequences. In hope of finding a clay mineral that might have reacted with calcite to form laumontite (section 6.2.1.3.), sandstone units I and II were also analyzed. It was speculated that unit II, in particular, might retain relics of the precursor mineral, in specimens that contain appreciable amounts of andesite, but not enough to have brought about reactions leading to the formation of laumontite (section 6.1.2.)

6.5.1. Analytical Procedures

The minerals were identified by x-ray diffraction patterns obtained from oriented specimens and different size fractions after various diagnostic treatments. Sample dispersion, separation, and preparation were essentially performed according to the procedure outlined by Lippmann and Rothfuss (1980). The sandstone samples were crushed and the 125-1000 micron fraction separated by wet-sieving, thoroughly rinsing the stack of sieves with water to ensure that no fine-grained splinters were added to the clay fraction by mechanical destruction of originally coarser constituents. The particles were physically dispersed in the 125-1000 micron fraction by vigorously shaking it in distilled water for approximately 48 hours; neutral pH had previously been obtained by adding a few drops of dilute ammonia. The sample and newly formed suspension were placed in a graduated cylinder and separated into 3 size fractions (<2, 2-6.3 and 6.3-20 microns) by settling in water. The separated fractions were oriented by allowing suspensions to dry slowly on a glass slide. For each sample and size fraction, some slides were treated by heat and ethylene glycol prior to x-ray examination. This required



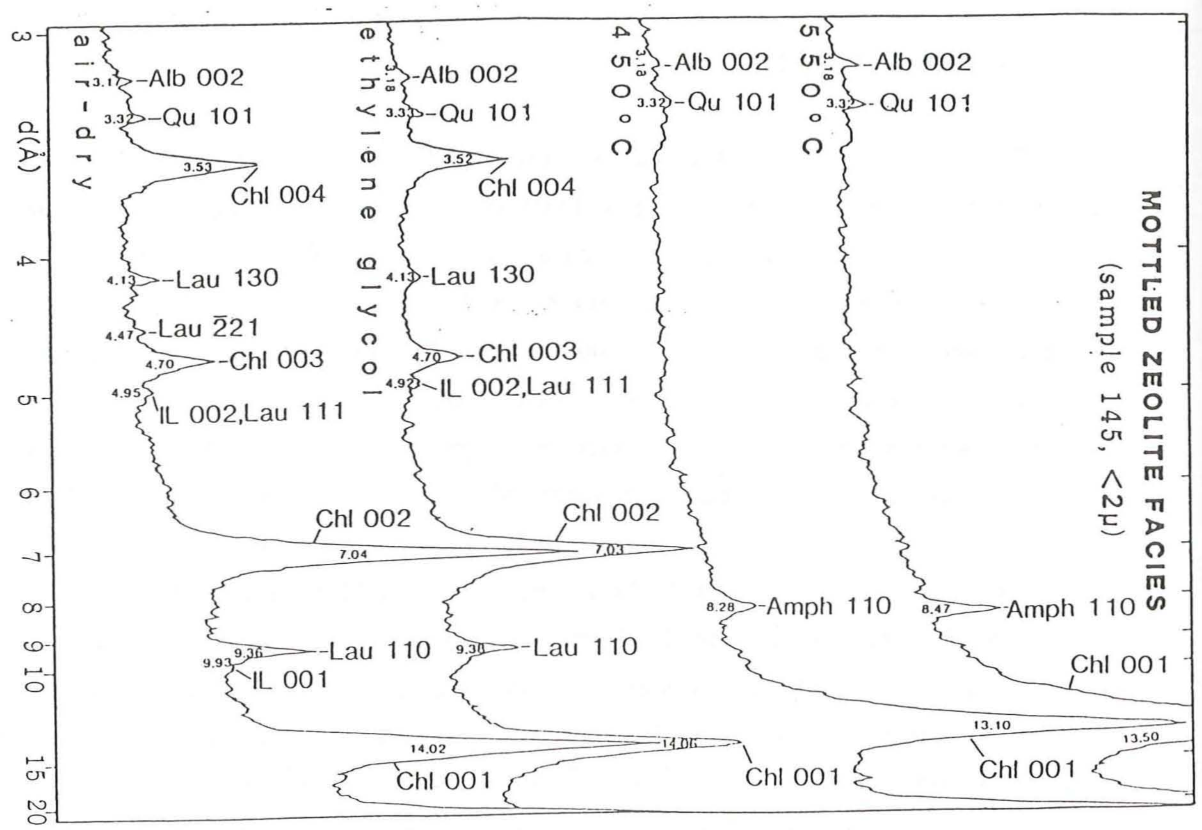
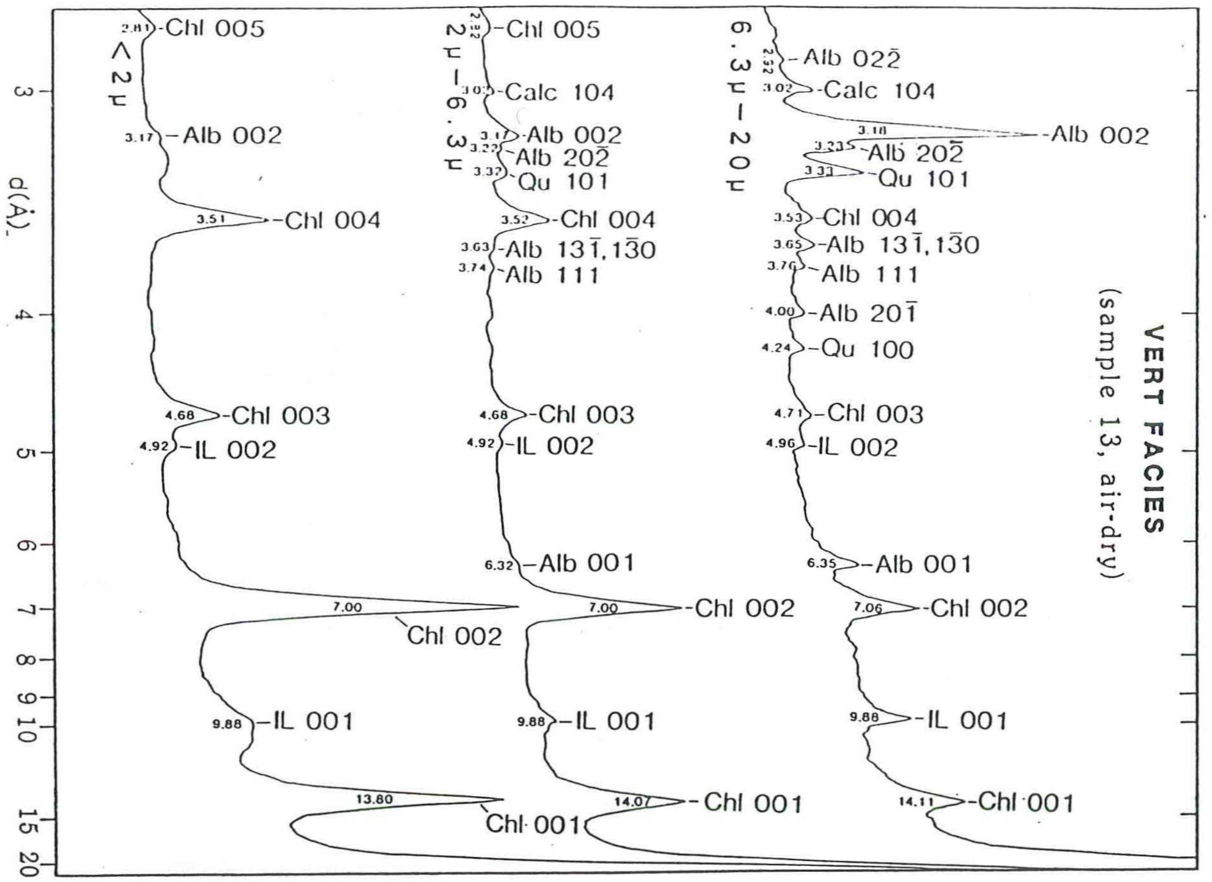


Fig. 29. X-ray diffraction patterns of oriented specimens separated from mottled sandstones of autochthonous unit (3a), for different size fractions (left) and after various diagnostic treatments (right).



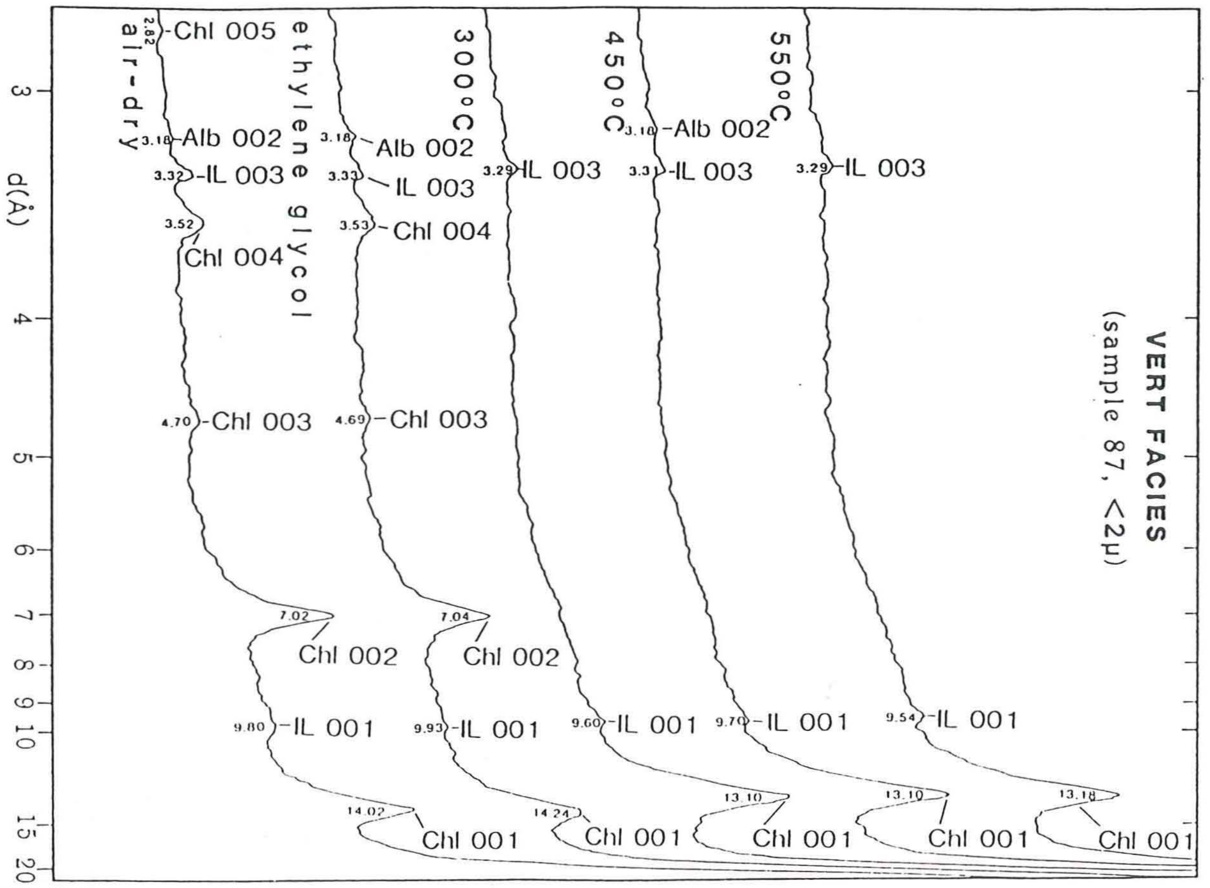


Fig. 30. X-ray diffraction patterns of oriented specimens separated from vert samples of autochthonous unit (3a), for different size fractions (left) and after various diagnostic treatments (right).

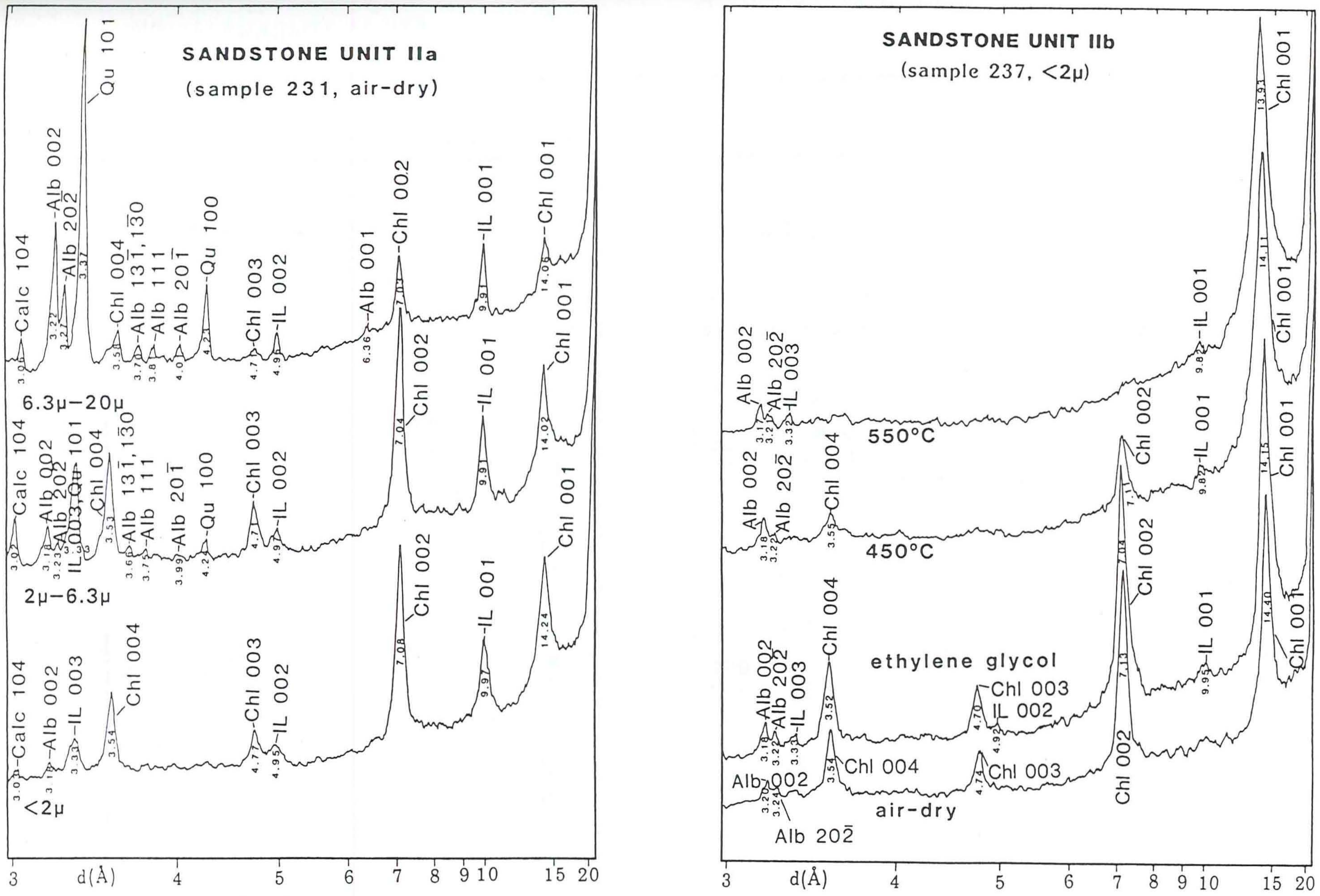


Fig. 31. X-ray diffraction patterns of oriented specimens separated from sandstones belonging to petrographically intermediate sandstone unit II, for different size fractions (left) and after various diagnostic treatments (right).

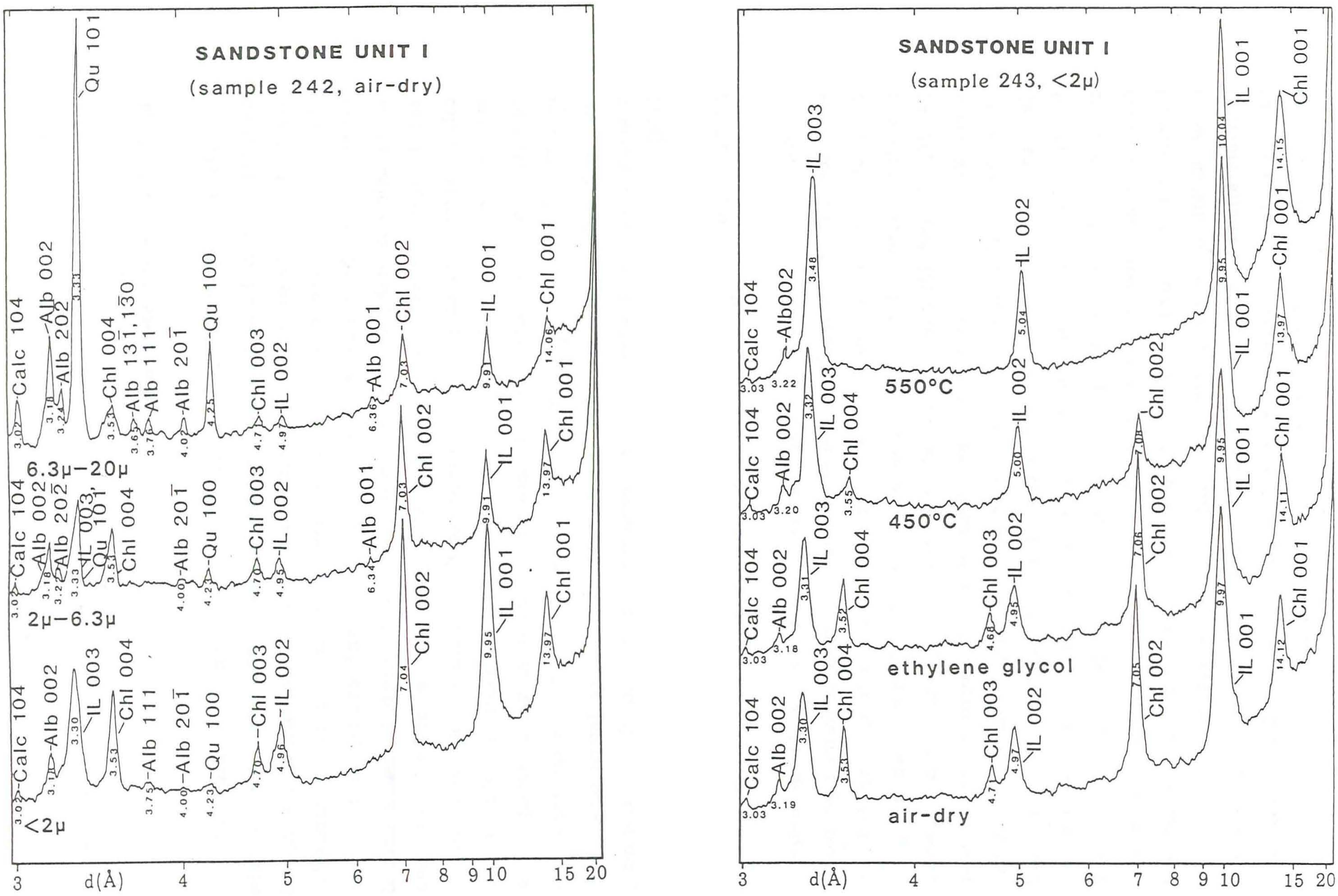


Fig. 32. X-ray diffraction patterns of oriented specimens separated from sandstones devoid of andesite in unit I, for different size fractions (left) and after various diagnostic treatments (right).

heating the specimens to 450°, 550°, and sometimes 300°C for approximately two hours, or exposing them to ethylene glycol vapor in a closed container overnight.

6.5.2. Characteristic Assemblages

The minerals identified by x-ray diffraction analysis in mottled sandstones comprise chlorite, laumontite, illite, amphibole, quartz, and albite (fig. 29). The characteristic minerals of the "vert facies" are chlorite, illite, albite, quartz, and calcite (fig 30). The most significant difference between the two metamorphic facies lies in the mutual exclusion of laumontite and calcite, so the same antipathetic relationship exists as that established in thin section. Sandstone units II and I (figures 31 and 32) may both contain chlorite, illite, albite, quartz, and calcite, which is basically the same assemblage that characterizes the vert samples, but with more illite. As explained in section 6.2.1.3., apparently the original montmorillonite has been mostly transformed to chlorite, via corrensite or a swelling chlorite. The clay minerals that have been identified by x-ray analysis in associated shale partings are illite, chlorite, and one or more interstratified clay minerals consisting of layers of illite, montmorillonite, and chlorite (Aprahamian, 1974).

6.5.2.1. Chlorite

An abundant mineral in the clay fraction is a non-swelling chlorite which is easily identified by its regular 00*l* series of basal reflections. It forms a prominent constituent in all sandstone samples and most size fractions. The lack of expandable layers and an additional reflection near 30 A° (not shown in figures 29, 30, 31, and 32) attests to the absence of corrensite, which is a diagnostic interstratified clay mineral found in geothermal areas at temperatures ranging from 95° to 230°C, often in association with laumontite (Kübler, 1973a, 1973b). In the Taveyanne Sandstone, corrensite occurs conjointly with laumontite (Lippmann and Rothfuss, 1980) and is succeeded at higher rank by chlorite, in rocks that are characterized by prehnite and pumpellyite (Kübler et al., 1974). Apart from some occurrences of corrensite (Aprahamian, 1974; Stalder, 1979), chlorite coexists with laumontite in the transitional facies of the Champsaur, where the latter is inferred to be metastable in the presence of incipient prehnite and pumpellyite. It is therefore assumed that the positive correlation between laumontite and corrensite is valid only in the absence of prehnite and pumpellyite, possibly because the decomposition of corrensite occurs prior to that of laumontite.

6.5.2.2. Laumontite

Lippmann and Rothfuss (1980) have shown that laumontite may also occur in the clay fraction of the Taveyanne Sandstone and similar mottled sandstones of Jugoslavia. In the mottled laumontite facies of the Champsaur Sandstone, it was regularly detected in all analyzed size fractions by the present author too. A preliminary examination of spotted sandstone samples taken from the **Briones Sandstone** also confirmed its occurrence in fractions ranging from 2-20 microns, and below.

6.5.2.3. Calcite

Whereas calcite is missing in all samples that contain laumontite, in most other samples it occurs in size fractions larger than 2 microns. During the formation of laumontite, the consumption of calcite in the original marl might have occurred by a process similar to reactions (3) and (4), both of which require a clay mineral and produce laumontite.

6.5.2.4. Illite

Illite may occur subordinately in all samples and size fractions. Due to unfavorable geochemical factors (Kübler, 1973a), and because the (110) reflection of laumontite partly overlaps the first-order basal reflection of illite, the "crystallinity" of illite cannot be determined in sandstones belonging to unit 3, i.e. in specimens containing substantial amounts of andesite. This would have to be undertaken in sandstones of the more internal units, where illite is sufficiently abundant and its first-order basal reflection adequately developed. It was not attempted, however, because Stalder (1979) has already successfully determined the "crystallinity" of illite for 13 samples that were collected from *shale* partings in the Champsaur; the values of 4.0 - 4.2 mm are indicative of the diagenetic stage. By contrast, the "crystallinities" of 5-9 mm determined by Aprahamian (1974) led him to place the zeolite facies of the Champsaur Sandstone partly or wholly above the anchizone.

6.5.2.5. Albite, quartz, and amphibole

All sandstone samples contain variable amounts of detrital quartz and plagioclase, the amounts of which generally rise with increasing grain size. In specimens heated to 450° and 550°C, a reflection close to 8.5 A° was often detected in laumontite facies rocks and ascribed to the (110) reflection of amphibole; it is presumably the destruction of chlorite and laumontite that renders this reflection more conspicuous in heated specimens.

6.6. Geochemistry of Graywacke Specimens

Whole-rock powders from 5 vert and 10 mottled sandstone specimens of the autochthonous unit were chemically analyzed for their major-element concentrations by the procedure outlined in section 3.2.2. Again, the vert samples were taken from sandstone beds intercalated in shale. The chemical compositions are listed and the two sets of data compared in table X. Additional information concerning the modal compositions of these sandstones may be obtained from tables V and VII. The clay-mineral contents of some of the chemically analyzed samples are furthermore shown in figures 29 and 30.

The most significant variation is shown by CaO and CO_2, both of which correlate positively with the amounts of modal calcite. In the "vert facies", these values are conspicuously more variable and, when averaged, higher than those determined in mottled rocks. This is due to the introduction of variable amounts of calcite from the adjacent marls.

Another major compositional disparity between the two metamorphic facies is seen in the amounts of H_2O+ which are generally higher in mottled rocks. The additional water was in all likelihood extracted from interstitial solutions and bound to the hydrous calc-silicates that characterize these rocks. Laumontite is volumetrically much more significant than either prehnite or pumpellyite. Both as replacement of calcic plagioclase and clay minerals, the formation of laumontite requires substantial amounts of water; equations (1) through (4) give an insight to the volumes of water involved.

When the concentrations of Fe_2O_3 and MgO are averaged and compared, the mottled graywackes appear enriched in both, in particular Fe_2O_3; on the other hand, some samples are slightly depleted in FeO. These differences are difficult to interpret, presumably because they are due to various factors, such as the presence of prehnite and pumpellyite, the better preservation of augite, as well as the dissimilar nature and larger amounts of chlorite. Pumpellyite and prehnite might have accommodated some of the excess Fe_2O_3, the former also MgO. Since in the mottled rocks augite is more preserved and not replaced by calcite (only by chlorite), its preservation would tend to retain some MgO, but also some FeO.

Table X. Major-element compositions of sandstones metamorphosed to the vert (right) and mottled laumontite facies (left).

	mottled facies										"vert" facies				
sample	77	107	145	159	166	173	204	205	206	224	9	13	18	49	87
SiO_2	63.59	59.18	63.59	60.54	61.12	58.74	62.84	62.98	62.84	63.35	70.61	66.72	60.92	60.36	57.96
TiO_2	0.76	0.78	0.55	0.69	0.65	0.74	0.62	0.64	0.55	0.52	0.38	0.47	0.45	0.51	0.84
Al_2O_3	13.53	15.66	14.71	15.26	15.07	16.41	14.55	14.42	14.80	15.44	12.94	14.02	12.78	13.67	14.58
Fe_2O_3	3.94	4.69	2.86	2.90	3.22	4.69	3.06	3.55	2.74	2.10	1.27	1.59	1.91	1.65	3.02
FeO	2.27	2.66	2.30	2.26	2.05	2.44	2.29	2.38	2.25	2.75	2.43	2.97	2.10	2.39	3.61
MnO	0.11	0.11	0.10	0.11	0.13	0.11	0.09	0.10	0.09	0.10	0.06	0.09	0.15	0.14	0.15
MgO	2.20	2.88	2.25	1.98	2.27	2.53	2.32	2.40	2.16	2.17	1.84	1.71	1.29	1.87	2.46
CaO	3.79	4.16	4.24	5.78	4.88	3.80	4.33	3.95	4.59	4.17	1.85	2.45	7.38	7.19	6.83
Na_2O	2.77	3.68	2.63	3.16	4.58	3.29	3.12	2.82	2.76	3.53	3.35	3.90	2.69	2.98	2.54
K_2O	2.34	2.16	1.87	1.86	0.98	2.45	2.22	2.31	2.06	2.22	2.38	2.64	2.94	2.51	1.83
P_2O_5	0.16	0.16	0.15	0.22	0.18	0.18	0.15	0.15	0.15	0.15	0.08	0.12	0.10	0.12	0.24
H_2O+	4.04	4.13	4.86	5.03	4.42	4.47	4.20	4.43	4.97	3.52	2.62	2.49	3.83	3.07	3.34
CO_2	----	----	----	0.41	0.64	----	0.32	----	0.40	0.08	0.78	1.08	3.60	3.61	2.58

Chlorite is more abundant in the mottled samples than in the vert samples where it is partly proxied by calcite. Larger amounts of chlorite might therefore entail larger quantities of MgO, FeO, and Fe_2O_3. Qualitative microprobe analyses show that the chlorite occurring in the mottled facies is strongly depleted in iron (section 6.2.3.), so this variation would primarily concern MgO.

It is thought that, within a finite flysch succession of the Champsaur, all metamorphosed graywackes were originally characterized by similar bulk rock compositions. Particularly SiO_2, TiO_2, Al_2O_3, MnO, Na_2O, K_2O, and P_2O_5 display no marked divergence between the two metamorphic facies, and little internal variation within a given facies (cf. Martini, 1968). The variations lie within the range to be expected from random spot sampling of turbidite successions, which are inherently characterized by lithological variations of some sort. It is therefore assumed that minor deviations in CaO, CO_2, H_2O+, Fe_2O_3, MgO, and FeO between the two facies gradually arose during progressive metamorphism. Recall that original bulk composition is apparently not a factor that governs the local distribution of the vert and mottled facies assemblages. Rather, it is concluded that the disposition of associated carbonates, marls, and faults determines the metamorphic course taken by the graywackes, by initially creating a CO_2-rich environment and impregnating the rocks with calcite (section 6.3.).

The graywacke compositions have been graphically represented in the triangular ACF diagram (fig. 33). The most apparent compositional transformation undergone by the vert samples is CaO enrichment. Due to the irregular addition of metasomatic calcite, the compositions diverge away from the mottled rocks of

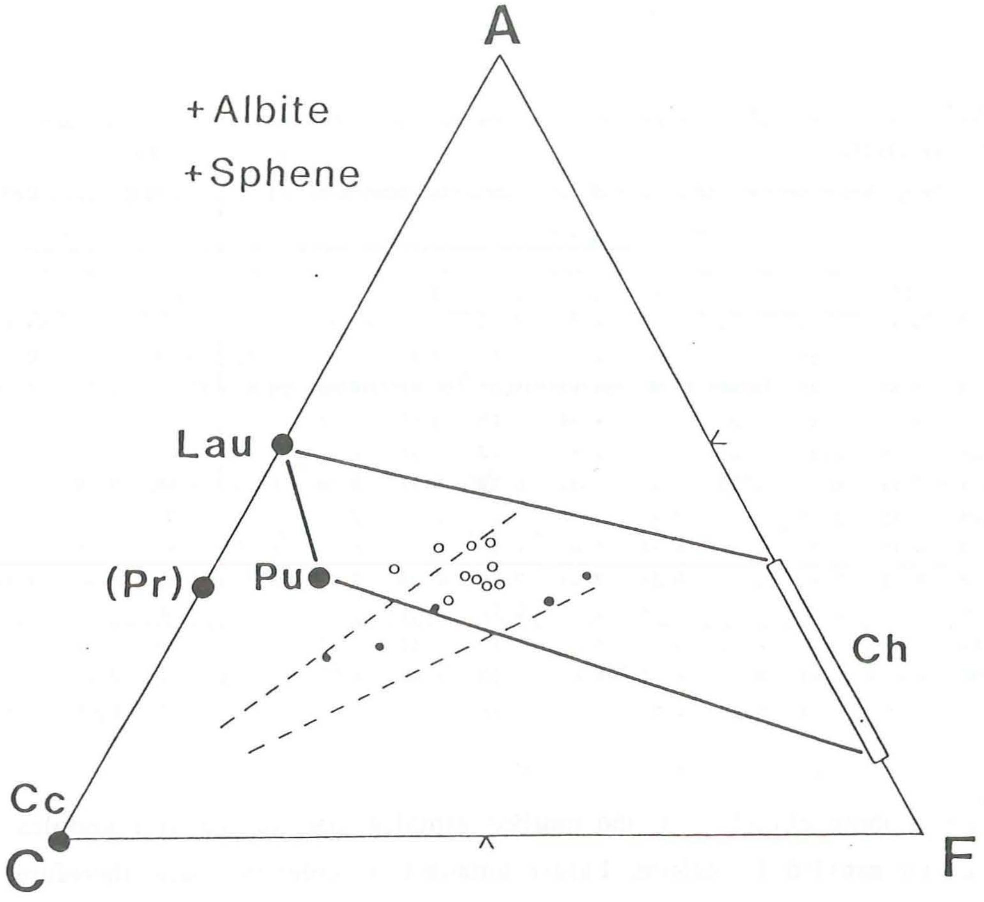


Fig. 33. Graphical representation of sandstone compositions (table X) in triangular ACF diagram, with heavy tie-lines joining compositions of minerals that occur abundantly in mottled rocks. The A, C, and F values were calculated by the procedure outlined by Mason (1981) and corrected for all accessories except calcite. The compositions of mottled sandstones are indicated by open circles, those of the vert samples by filled circles. The dashed lines delimit the vert samples and are intended to emphasize the compositional scatter towards calcite. Lau=laumontite; Pu=pumpellyite; Pr=prehnite; Ch=chlorite; and Cc=calcite.

approximately the same original composition. By contrast, the zeolite facies rocks lie well within the compositional field that is delineated by the constellation of tie-lines joining their secondary minerals; it is therefore likely that their compositions are closer to those of the original sediment. Note that some of the vert samples have retained a similar composition, accommodating only negligible amounts of metasomatic calcite; and yet they are characterized by a different assemblage. Once again, this is taken as an indication that the diffusion of CO_2 and precipitation of calcite control the development of potential phases, not necessarily the bulk chemical characteristics of the original sediment.

6.7. Estimation of Depth of Burial

Finally, an attempt is made at estimating the temperatures and effective load pressures to which the Champsaur Sandstone was subjected in the course of its

burial by higher, originally more internal nappes. Concerning the uppermost stability limit of laumontite, experimental studies have shown that, at pressures up to 3 Kb, it dehydrates to wairakite above temperatures of approximately 240-300°C; at pressures exceeding 3 Kb, it gives way to lawsonite (Coombs et al., 1959; Koizumi and Roy, 1960; Liou, 1971a). The lowermost possible stability limit is established by the recent discovery of laumontite precipitates at Sespe Hot Springs, California, which illustrates that, under favorable physico-chemical conditions, laumontite can crystallize directly from aqueous solutions, at atmospheric pressure and at temperature as low as 43°C - independantly - that is, without the agency of a precursor mineral such as stilbite or heulandite (McCulloh et al., 1981). In geothermal oil fields, however, laumontite commonly does not appear at temperatures below 100° C (Iijima and Utada, 1966; Averyev et al., 1961; Sigwvaldason, 1963), and its crystallization temperature may have been as high as 200° C in the sedimentary section at Wairakei, New Zealand, where its formation occurred through the breakdown of heulandite (Coombs, 1961).

No matter what the initial temperature of formation, the partial decomposition of laumontite in the Champsaur Sandstone suggests that, with rising temperature, its stability limits had finally been breached. In the average graywacke specimen, laumontite is partly replaced by pumpellyite and incipient prehnite, and its close companion, corrensite, has partly disappeared. Recall that prehnite is the last phase to have formed, partly as replacement of laumontite by means of reaction (10) which is considered to take place at temperatures exceeding 200° C (Liou, 1971b). Similarly, field studies have shown that corrensite does not persist above temperatures ranging from 148°C in geosynclines to 230°C in active geothermal fields (Kübler, 1973b).

One may therefore assume that the Champsaur Sandstone was subjected to temperatures exceeding 200° C. More specifically, it is thought that, adjacent to fissures, the prehnite-pumpellyite facies was truly reached, the assemblages of which are stable above approximately 240° C (see Coombs, 1971; and Liou, et al., 1987). Assuming a surface temperature of 20° C and a normal geothermal gradient of 30°C/km (Elter et al., 1969; Kübler et al., 1974), these temperatures would correspond to burial depths of at least 6000 or 7300 m. The temperatures and corresponding depths might have been significantly lower if CO_2 or solutes were present in the fluid phase (Coombs, 1971). On the other hand, considering that the geothermal gradient might have been somewhat lower, say, around 20°C/km (Sawatzki, 1975), which is a reasonable assumption for a region inferred to have undergone rapid subsidence in response to thrust loading, the effective depth of burial might have been significantly higher, too, in the order of at least 9000 or

11000 m. In any case, assuming that the increase in overburden pressure was approximately 250 bars/km, it follows that the depth of burial cannot have exceeded 12000 m, where 3 Kb and the stability field of lawsonite is reached. This places tighter constraints on the lowermost possible geothermal gradient, namely 15°C/km for 200°C, or 18.3°C/km for 240°.

6.8. Conclusions

The diagnostic, carbonate-free assemblage of the Champsaur Sandstone comprises laumontite, pumpellyite, prehnite, albite, chlorite, and sphene, often with minute quantities of a micaceous mineral, possibly sericite. The secondary mineral associations are thus characteristic of the transition from zeolite- to prehnite-pumpellyite facies assemblages in the external Western Alps. Though it was not possible to determine regional metamorphic zonations by way of diagnostic mineral associations in the limited volcaniclastic outcrops of the Champsaur, extensive variations have been delineated on the basis of illite "crystallinities" in sediments bordering the crystalline massifs of Belledonne and Pelvoux (Aprahamian, 1974). The variations observed in this area are consistent with the recognition that metamorphism generally increases in grade toward the more internal zones of the Alps, due to the variation in overburden pressure and thickness of the overlying nappes. However, whereas in the Taveyanne Sandstone metamorphic grade decreases progressively from E to W along the alpine arc (Kübler et al., 1974), a substantial departure from this pattern may be deduced from the secondary mineral associations of the Champsaur Sandstone, which turn out to be of higher rank than those that characterize the westernmost occurrences of the Taveyanne Sandstone. The inferred overburden pressure diverges even more so from that of volcaniclastic deposits farther to the south, at St. Antonin and Clumanc, which, by contrast, have hardly been affected by subsequent burial metamorphism, if at all. One must therefore reckon with a former local protrusion of nappes in the general vicinity of the Champsaur.

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