RENDICONTI Società Italiana di Mineralogia e Petrologia, 38 (3): pp. 1361-1386
Comunicazione presentata alla Riunione della SIMP in Rende-Cetraro (Cosenza) il 27-10-1982

DIAGENETIC PROVINCES OF THE VERRUCANO LOMBARDO AND VAL GARDENA SANDSTONES (PERMIAN), SOUTHERN ALPS, ITALY

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ABSTRACT. — Diagenetic sequences and porosity in the arkosic and lithic-rich Verrucano Lombardo and Val Gardena Sandstones in northern Italy are strongly controlled by framework mineralogy and tectonic history. These stratigraphically equivalent Permian age sandstones were deposited in various nonmarine environments during an early stage of rifting at the base of the Alpidic cycle. They consist dominantly of quartz, feldspars, and acidic to intermediate volcanic rock fragments. Source terranes for these sandstones consist of the underlying Permian volcanic and terrigenous rocks and the low- to medium-grade metamorphic rocks of the pre-Permian crystalline basement.

Three distinct diagenetic provinces have been differentiated based on (1) the presence and nature of carbonate cement and/or replacement, (2) the presence of quartz cement, (3) the presence of kaolinization of detrital K-feldspar, and (4) the degree of recrystallization of detrital clay matrix. Province A, located in the Carnia region, includes sandstones characterized by extensive replacement dolomite, common quartz overgrowths, lack of kaolinized K-feldspars and a locally abundant unrecrystallized matrix. Sandstones of Province B are located in the Dolomite region and are characterized by the presence of both poikilotopic calcite and ferroan dolomite, lack of common quartz overgrowths, extensive kaolinization of detrital K-feldspar, and an unrecrystallized matrix. Sandstones of Province C occupy the Lombardy region and are easily recognized by the absence of carbonate phases, quartz overgrowths, and authigenic kaolinite, and by the presence of an abundant, highly recrystallized clay matrix.

Primary porosity has been completely destroyed by mechanical and chemical compaction in conjunction with quartz cementation and carbonate replacement. Some secondary porosity has been created through the dissolution of replacement carbonate, especially in the sandstones of Provinces A and B, but is not sufficiently developed to form an effective pore system.

Introduction

The stratigraphically equivalent Permian age Verrucano Lombardo and Val Gardena Sandstones of the Southern Alps of Italy crop out in an area bordered on the west by Como Lake and on the east by the Carnia region (fig. 1). Regional variations in mineral composition and structural deformation of this red bed sequence have resulted in several different diagenetic sequences. These sandstones, therefore, offer an opportunity to demonstrate mineralogical and tectonic control on diagenesis in sandstones during burial.

With the above concept in mind, an investigation of the Verrucano Lombardo and Val Gardena Sandstones was undertaken with the major objectives to: (1) delineate gross diagenetic provinces, (2) develop a diagenetic sequence for each province, (3) determine the origin of red coloration of the sandstones, and (4) determine the origin and distribution of carbonate phases.

Methods

Thin sections of thirty-five samples from the Val Sassina, Pizzo della Nebbia, Val Sanguigno, Butterloch, San Martino in Badia, Danta, and Paluzza stratigraphic sections (fig. 1) were analyzed to determine detrital

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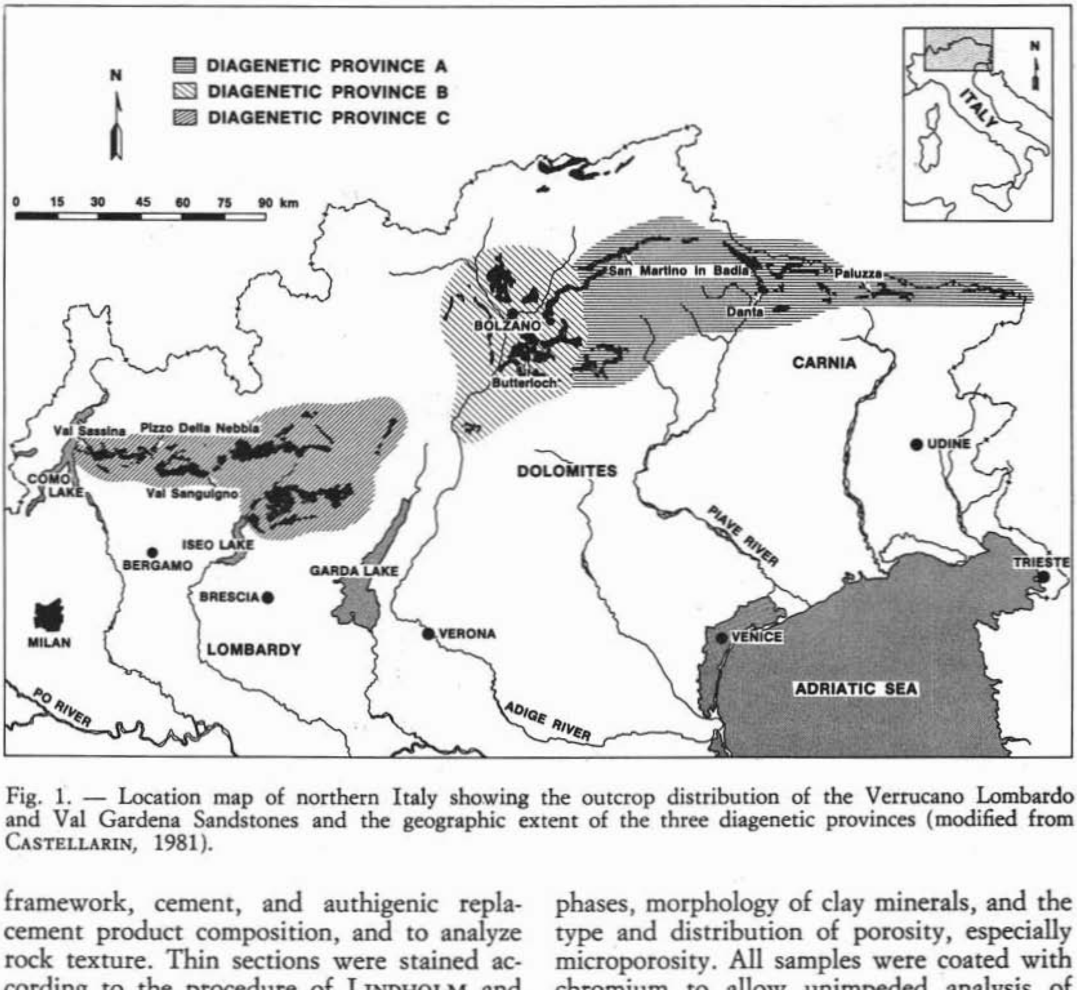

Fig. 1. — Location map of northern Italy showing the outcrop distribution of the Verrucano Lombardo and Val Gardena Sandstones and the geographic extent of the three diagenetic provinces (modified from CASTELLARIN, 1981).

framework, cement, and authigenic replacement product composition, and to analyze rock texture. Thin sections were stained according to the procedure of LINDHOLM and FINKELMAN (1972) to determine the mineralogy and iron content of carbonate phases.

X-ray diffraction analyses were performed on bulk samples and the < 2 micrometer-size fraction of the sandstones. Analyses of the clay-size fraction were conducted on both air-dried and ethylene glycol-treated samples to aid in identification of swelling and mixed-layer clays. Quantification of the clay minerals follows the scheme of SCHULTZ (1960, 1964) and the composition of mixed-layer clays was determined by the methods of HOWER (1981).

Twenty samples were analyzed with a JEOL JSM-35C scanning electron microscope (SEM) equipped with a Tracor Northern TN-2000 energy dispersive spectrometer (EDS) to determine textural relationships (paragenetic sequence) between authigenic phases, morphology of clay minerals, and the type and distribution of porosity, especially microporosity. All samples were coated with chromium to allow unimpeded analysis of the energy dispersive spectra without significant loss of visual resolution. Identification of authigenic minerals was accomplished by a combination of crystal morphology and elemental composition as determined via semi-quantitative energy dispersive X-ray analysis. Criteria for differentiating detrital from authigenic clays are those of WILSON and PITTMAN (1977).

Regional geology

The Verrucano Lombardo and Val Gardena Sandstones were deposited during an early stage of rifting at the base of the Alpidic cycle in the Southern Alps (CASSINIS et al., 1979). The sandstones unconformably overlie basement rocks that were subjected to Hercynian orogenesis and that are rep-

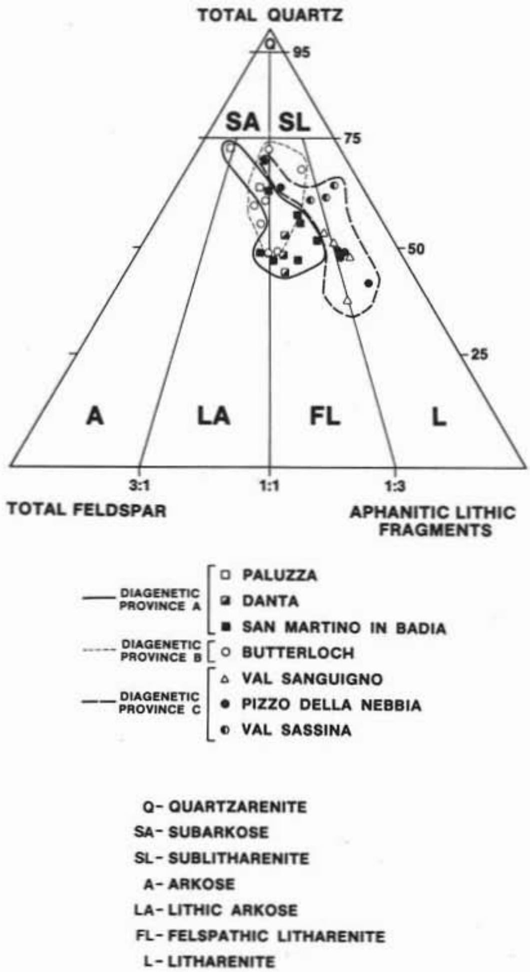

Fig. 2. — *QFL* triangular diagram comparing detrital modes of Verrucano Lombardo and Val Gardena sandstones from seven stratigraphic sections. Sandstone classification scheme is from FOLK (1974 a).

resented by pre-Permian metamorphic rocks, Permian age « Piattaforma Atesina » volcanic rocks, and Permian age terrigenous rocks of the Collio Formation. The latter Permian age rocks were deposited during the final stage of the Hercynian orogenesis.

In the Dolomites and Carnia regions, east of the Adige Valley, the Val Gardena Sandstone is overlain by the Permian Bellerophon Formation which is a carbonate-evaporite sequence. The contact between the two formations is transitional and is delineated by a gradual decrease of terrigenous material and an increase in evaporites upwards. In the Lombardy region to the west of the Adige Valley, the Verrucano Lombardo Sandstone is overlain by marine and paralic rocks, mostly quartzose sandstones and siltstones, of the Triassic Servino Formation.

Depositional facies and environments

The Verrucano Lombardo and Val Gardena Sandstones consist predominantly of fluvial facies, with some lagoonal and marine facies intercalated in the middle part of the section in the Adige Valley area (Butterloch section). In the western Lombardy region the formation is composed of less than 100 meters of medium- to coarse-grained quartz conglomerates that represent piedmont-slope deposits (ASSERETO et al., 1973). In the central Lombardy region the rocks form an irregular alternation of sandy conglomerates, sandstones, and siltstones that are interpreted as the proximal and distal facies of a piedmont plain upon which braided streams traversed (ASSERETO et al., 1973). Thickness of the formation in this area reaches up to several hundred meters and is controlled by basement topography. In the Dolomites and Carnia regions the sequence consists predominantly of siltstones and cross-bedded sandstones that comprise the alluvial-plain facies of a meandering river system (ASSERETO et al., 1973). Throughout the entire study area scattered caliche horizons composed of carbonate nodules occur near the top of the formation in siltstones and mudstones which overlie the more massive sandstones.

Detrital mineralogy

FONTANA and ZUFFA (in press) have shown that the Verrucano Lombardo and Val Gardena Sandstones are litharenites, feldspathic litharenites and lithic arkoses (fig. 2) according to the classification of FOLK (1974 a). Source terranes for the sandstones consist of the underlying Permian volcanic and terrigenous rocks (« Piattaforma Atesina » and Collio Formation) and the low- to medium-grade metamorphic rocks of the pre-Permian crystalline basement.

Quartz is the most abundant mineral and comprises 20 to 55 percent of the bulk

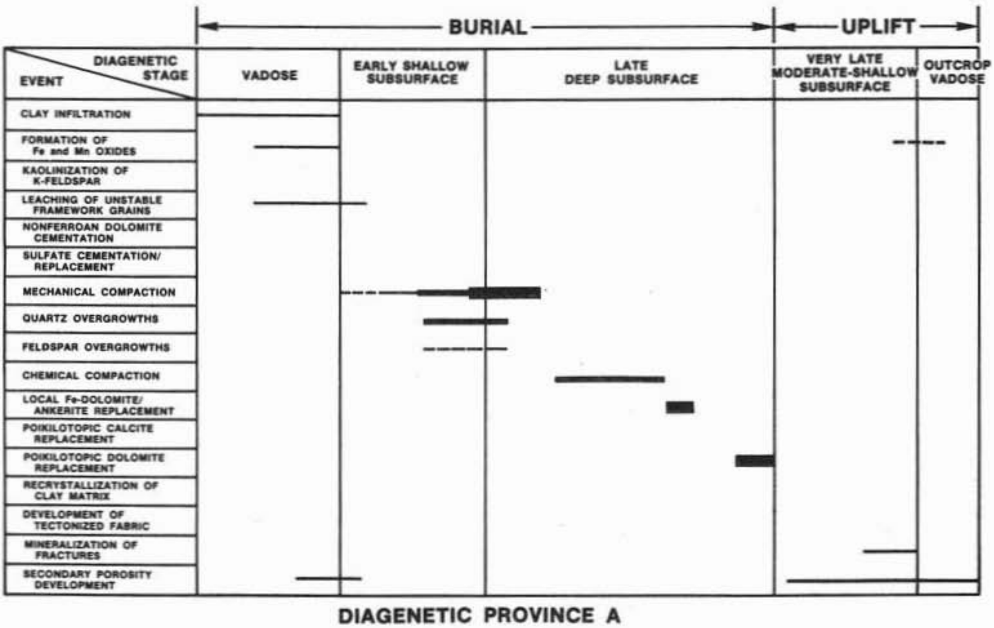

Fig. 3. — General diagenetic stages and events affecting Val Gardena sandstones from Province A. Time increases towards the right; depth increases towards the right until uplift.

sandstones (35 to 75 percent of the framework grains). Most of the quartz grains are subangular, clear, and few contain mineral inclusions. They are predominantly monocrystalline with straight extinction but some grains have undulous extinction.

Feldspar (potassium feldspar plus plagioclase) content of the bulk sandstones ranges from 4 to 29 percent. Plagioclase is generally more abundant than potassium feldspar except in sandstones from the Butterloch section where potassium feldspar is the dominant feldspar.

Mica content ranges from 0 to 10 percent and the mica flakes are commonly oriented parallel to bedding. Muscovite is more abundant than biotite with the biotite commonly altered or replaced by iron-oxides.

Lithic fragments consist of volcanic, low- to medium-grade metamorphic, and sedimentary rock fragments. Sedimentary rock fragments (sandstone and siltstone) are rare and are present only near the top of the sequence. Volcanic rock fragments comprise 2 to 36 percent of the bulk sandstones and consist of lavas and ignimbrites with a composition ranging from rhyolitic to andesitic. The groundmass of these fragments exhibits felsitic, microfelsitic, or granopheric texture with phenocrysts of quartz, plagioclase, sanidine, and biotite. In addition, the groundmass is commonly stained or partially replaced by iron-oxides related to deuteric alteration of various cooling units (Ghezzo, 1967). Metamorphic rock fragments comprise less than 10 percent of the bulk sandstones. They consist of epizonal phyllites and gneiss composed generally of quartz, albite, and sericite-muscovite.

Diagenetic provinces

Three distinct diagenetic provinces have been recognized in the Lombardy, Dolomites, and Carnia regions of northern Italy from seven stratigraphic sections of the Verrucano Lombardo and Val Gardena Sandstones. The term « diagenetic province » is used to signify a geographic region in which sedimentary rocks are characterized by similar diagenetic features and history. The diagenetic provinces of the Verrucano Lombardo and Val Gardena Sandstones, hereafter referred to simply as provinces, are given letter designations in preference to geographic names to avoid ambiguity if they are expanded by future work. Province A is located in the eastern third of the study area and includes the Paluzza, Danta, and San Martino in Badia sections. Province B is typified by the Butterloch section located in the vicinity of Bolzano in the center of the study area. Province C occupies the western third of the area and includes the Val Sanguigno, Pizzo della Nebbia, and Val Sassina sections (fig. 1).

The Verrucano Lombardo and Val Gardena Sandstones from the three provinces are differentiated on the basis of (1) the presence and nature of carbonate cement and/or replacement, (2) the presence of quartz cement, (3) the presence of kaolinization of detrital k-feldspar, and (4) the degree of recrystallization of detrital clay matrix. It should be emphasized that these are not the only diagenetic features in the Verrucano Lombardo and Val Gardena Sandstones, but that they best serve to distinguish among the three provinces. Furthermore, not all sandstones within a single province are petrographically identical. Some sandstones may display all the characteristics diagnostic of a given province, while others from the same or different stratigraphic sections may exhibit only a few.

Province A

Sandstones of Province A are characterized by extensive replacement dolomite, common quartz overgrowths, lack of kaolinization of detrital K-feldspar, and locally abundant unrecrystallized clay matrix. The complete diagenetic sequence for these sandstones is: (*a*) infiltration of clay matrix shortly after deposition; (*b*) dissolution of unstable framework grains and formation of iron and manganese oxides in the vadose environment; (*c*) formation of quartz and feldspar overgrowths simultaneously with mechanical compaction; (*d*) chemical compaction (pressure solution) in the moderate to deep subsurface; (*e*) minor replacement by Fe-dolomite/ankerite of detrital grains and matrix; (*f*) local late-stage dolomitization; (*g*) mineralization of local fractures; (*h*) dissolution of carbonate cements before or during uplift; and (*i*) outcrop weathering (fig. 3).

The Verrucano Lombardo and Val Gardena Sandstones represent mainly fluvial environments (ASSERETO et al., 1973; CASSINIS et al., 1979) in which finer-grained suspended sediment was efficiently separated from coarser-grained bed load. Detrital matrix was therefore probably absent from these sands during deposition, but shortly thereafter, while the sands were within a few meters of the surface, mechanical infiltration of clay associated with downward-percolating ground water resulted in localized concentrations of clay matrix. The distribution of infiltrated clay is not uniform within the sandstones; deposition was greatest above both the local water table and beds of low permeability which acted as barriers to further downward migration of ground water (WALKER, 1976; WALKER et al., 1978). The detrital nature of this clay is demonstrated in thin section by « pinch-outs » resulting both from deposition and from post-depositional compaction (fig. 4 *a*), and in samples examined with a scanning electron microscope (SEM), by the presence of a clastic texture in which the individual clay platelets are aligned parallel with the surface of the framework grains (fig. 6 *a*, *b*; WALKER et al., 1978). Clay infiltration is the first process acting to decrease the porosity and permeability of these rocks, but also affects later diagenetic processes in rocks where it reduces pore-fluid movement and inhibits the nucleation of quartz and feldspar overgrowths.

Iron and manganese oxides are common in sandstones of Province A, occurring in four textural relationships: (1) detrital oxides incorporated in ferruginous framework grains; (2) authigenic oxides associated with the early dissolution of chemically unstable framework grains; (3) extremely fine-grained authigenic oxides present as a stain; and (4) oxides associated with the outcrop weathering of iron-bearing phases. It is important to distinguish those oxides formed in the post-depositional environment from those transported to the depositional site as detritus. Commonly detrital oxides occur as stains on larger detrital grains, especially iron-rich volcanic rock fragments. They represent the product of oxidizing conditions that prevailed either in the source rock or during transportation to the present depositional site. These oxide coatings are easily recognized in thin section by their restricted

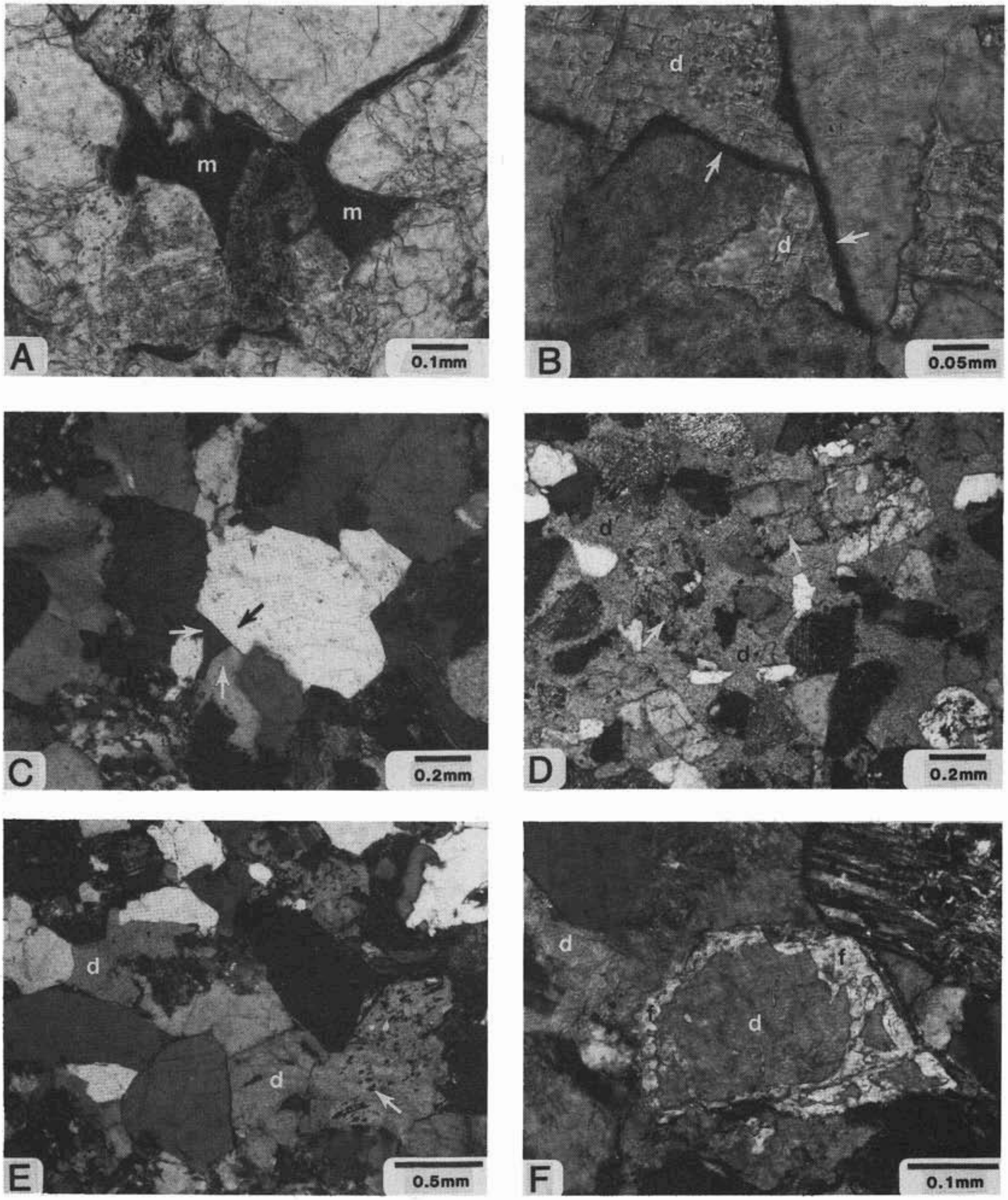

Fig. 4. — Photomicrographs of Val Gardena sandstones from Province A. - A. Detrital matrix (*m*) consisting of infiltrated clay that completely occludes intergranular porosity. « Pinch-out » of matrix is a result of both deposition and deformation during mechanical compaction. Compare with fig. 6 B. San Martino section, sample DF 1118. Plane light. - B. Thin authigenic iron oxide coatings (arrows) on detrital grains. Note that oxides are absent where grains have been partially replaced by dolomite (*d*). San Martino section, sample DF 1122. Plane light. - C. Silica cementation in the form of quartz overgrowths effectively destroys intergranular porosity, especially where several overgrowths (arrows) nucleate on adjacent quartz grains and coalesce to completely occlude pores. San Martino section, sample DF 1121. Crossed nicols with gypsum plate. - D. Late-stage poikilotopic ferroan dolomite (*d*) that has extensively replaced detrital grains (arrows) and clay matrix. There is little evidence remaining of the tight packing

occurrence on ferruginous framework grains.

Two distinct authigenic oxides have been recognized with the scanning electron microscope (SEM) based on crystal morphology and elemental composition. Iron oxide occurs as small spherical masses and star-shaped crystals (fig. 6 *d*) that are less than one micron in size. The apparent hexagonal symmetry of the star-shaped crystals suggests they are hematite, although confirming X-ray diffraction data were not obtained due to the small amount of material present. These iron oxides occur as linings of large moldic pores created by the dissolution of chemically unstable framework grains (fig. 6 *c*; TURNER, 1980), as coatings on framework grains (fig. 4 *b*), and in small patches between the cleavages of detrital mica. WALKER et al. (1978) clearly demonstrated that similar iron oxides were a product of very early dissolution of unstable ferromagnesium silicates in the oxygenated vadose environment. No doubt much of the iron oxide in the sandstones of Province A has a similar origin, especially those associated with the dissolution of detrital components.

The second authigenic oxide recognized contains either only manganese as the metal cation (probably pyrolusite) or manganese plus iron and has a reticulate or anastomosing morphology. Manganese oxides are not as widely disseminated as the iron oxides, possibly the result of a smaller amount of manganese-bearing minerals in the detritus. They occur as thin rims on framework grains, and apparently formed early in the vadose and oxygenated shallow subsurface diagenetic environments along with iron oxide.

Extremely fine-grained iron oxides comprise a stain which is disseminated throughout the sandstones, but which is concentrated in the infiltrated clay matrix due to the high surface tension and irreducible water associated with clay minerals. As suggested by WALKER et al. (1978), these stains are believed to consist of oxides which are either amorphous or composed of crystals too small to be viewed with a SEM because no discrete iron oxides have been detected in those sandstones with a dark red clay matrix.

Iron and manganese oxides similar to those described above are occasionally present as coatings on other authigenic minerals, most commonly quartz and iron-bearing carbonate. These oxides appear to be a very late alteration product and are possibly the result of surface weathering following uplift. Because the very early formation of iron and manganese oxides in the vadose and shallow subsurface environments (WALKER et al., 1978) and outcrop weathering are essentially the same process, the products may be difficult or impossible to distinguish.

The coloration of the sandstones is strongly controlled by the distribution of, and to a lesser extent, by the amount of iron oxide in the rocks. Both the detrital hematite and that associated with leached framework grains are only minor contributors to the red color of the rocks. They are abundant in some hand samples that are white or gray, but are rare or totally absent in others with a dark red color. The hematite stain has a more pronounced effect on rock color. The affinity of the stain for clay minerals results in the final color of the rock being strongly controlled by the amount of infiltrated clays in the sandstones. Those samples with substantial clay matrix invariably are red in both hand sample and thin section, while those with only a small quantity or no interstitial matrix are white or gray. It appears that the surface area of the oxides has more control over the final color of the rock than does the actual amount of oxides present in the sandstones. The abundant micrometer-sized hematite crystals associated with detrital volcanic rock fragments and leached framework grains may

that existed in this sandstone prior to dolomitization. Compare with figure 6 E. San Martino section, sample DF 1123. Crossed nicols. - E. Incipient replacement of framework grains by late-stage poikilotopic ferroan dolomite (*d*). Note remnants of partially replaced grains (arrow) in dolomite and the tight packing that was characteristic of these sandstones prior to dolomitization. San Martino section, sample DF 1121. Crossed nicols with gypsum plate. - F. Remnant detrital feldspar (*f*) that has been partially replaced by poikilotopic ferroan dolomite (*d*). This relationship suggests that the poikilotopic ferroan dolomite is a late-stage replacement of detrital components of the rock. San Martino section, sample DF 1122. Crossed nicols.

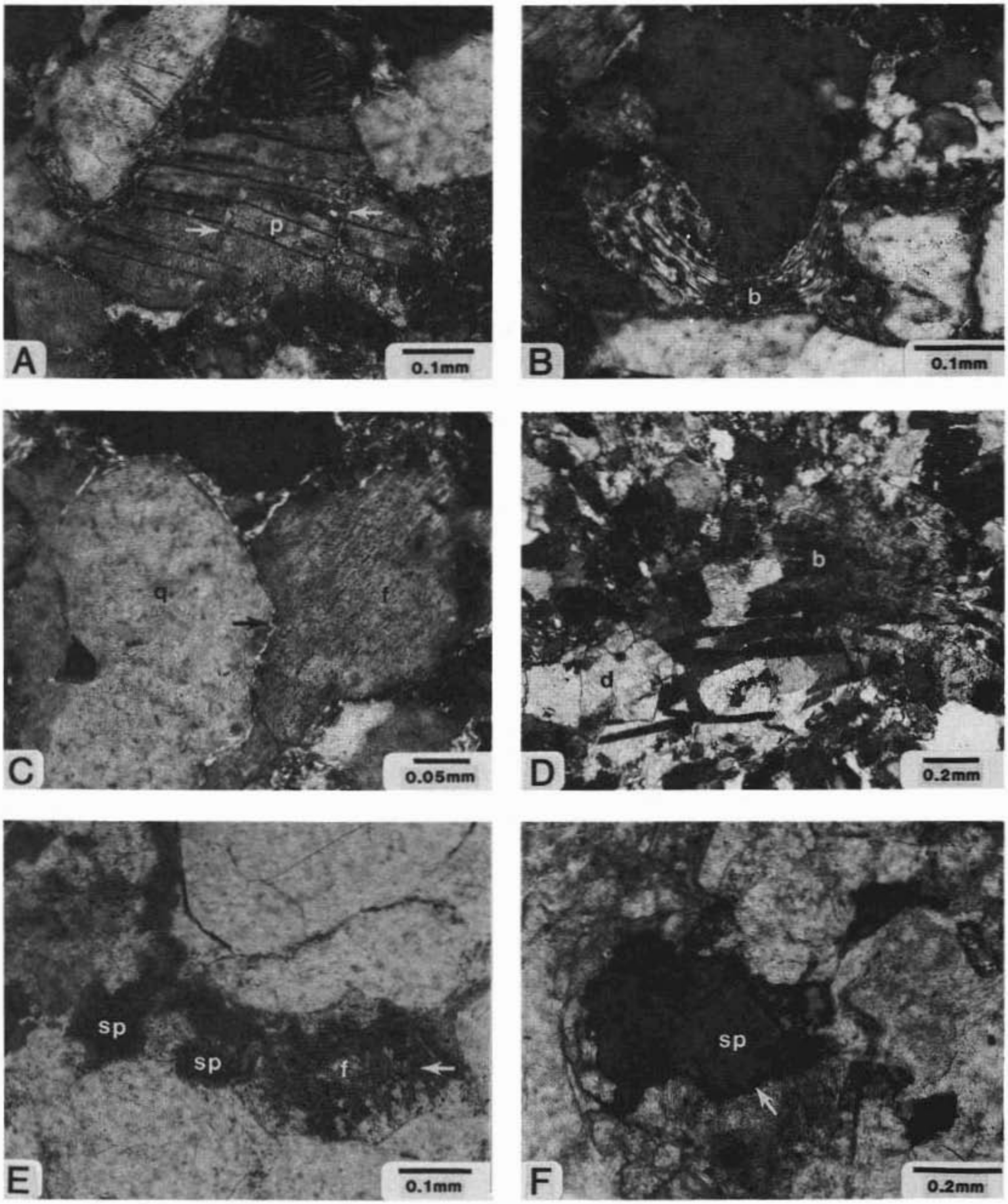

Fig. 5. — Photomicrographs of Val Gardena sandstones from Province A. - A. Detrital plagioclase grain (*p*) that has been fractured (arrows) as a result of mechanical compaction. San Martino section, sample DF 1119. Crossed nicols. - B. Detrital biotite (*b*) that has been highly deformed between more mechanically stable framework grains during mechanical compaction. San Martino section, sample DF 1119. Crossed nicols with gypsum plate. - C. Pressolved contact (arrow) between adjacent quartz (*q*) and potassium feldspar (*f*) grains. Chemical compaction (pressure solution) is the dominant agent of porosity destruction in the deep subsurface. San Martino section, sample DF 1119. Crossed nicols. - D. Equant ferroan dolomite (*d*) and bladed barite (*b*) filling late-stage fracture that is probably a result of tectonism associated with uplift. The occurrence of sulfates suggests mineralization proceeded in the presence of oxygenated meteoric waters. Paluzza section, sample DF 188. Crossed nicols with gypsum plate. - E. Secondary porosity (*sp*) created through the dissolution of replacement dolomite. Note

impart a local red color but are less effective in coloring the entire rock than the submicrometer-sized stain.

After the main period of oxide formation, but before substantial compaction, authigenic quartz, and to a lesser degree feldspar, nucleated on detrital grains as overgrowths. Silicate overgrowths are more prevalent in those samples without substantial clay matrix which apparently reduces porosity and permeability sufficiently to prevent free flow of formation waters, thereby retarding overgrowth nucleation. In some of the more matrix-free samples, quartz cementation effectively reduces porosity, especially where several overgrowths coalesce to completely occlude intergranular porosity (fig. 4 *c*).

Compaction is largely responsible for porosity destruction in sandstones of Province A, although quartz cementation is the dominant agent of porosity reduction in a few samples. Compaction and quartz cementation probably proceeded simultaneously until cementation began to wane with increased compaction as the sediments were progressively buried. Effects of compaction include fracturing of feldspar grains (fig. 5 *a*), kinking of ductile mica flakes (fig. 5 *b*), and chemical compaction (pressure solution) of quartz and feldspar grains (fig. 5 *c*). For the most part mechanical compaction is the main agent of porosity reduction in the shallow subsurface, while chemical compaction is the dominant diagenetic process in the deep subsurface (fig. 3), although these two processes no doubt temporally overlap to some extent. These features are less evident in the more completely cemented sandstones where compaction was prohibited by earlier quartz cementation.

After mechanical and chemical compaction had destroyed virtually all primary porosity, most sandstones of Province A remained essentially unaffected by diagenetic modifications until the initiation of late-stage dolomitization. A few sandstones, however, particularly those from the Danta section, were subjected to minor replacement by ferroan dolomite/ankerite before the onset of the main period of dolomitization. This diagenetic event is more characteristic of sandstones of Province B and is therefore discussed more fully in the following section. Late-stage dolomitization varies from massive replacement affecting the entire sample (fig. 4 *d*, 6 *e*, *f*) to incipient replacement in which only a few framework grains are affected (fig. 4 *e*). Many sandstones of Province A were unaffected by the late-stage dolomite. The dolomite contains variable amounts of iron and usually is poikilotopic with crystals up to 1 cm in diameter in the more massively replaced zones. Extensive dolomitization results in expanded fabric in which framework grains are « floating » in dolomite « cement » (fig. 4 *d*). This texture is typical of early poikilotopic calcite cements that precipitate in loose sands prior to compaction, thereby preventing further diagenetic modification of the sediment (PETTIJOHN, 1975). As far as is known, dolomite has not been previously recognized to exhibit a poikilotopic texture when precipitating into open pore spaces, but rather forms individual rhombic crystals. Petrographic evidence substantiates a late replacement origin for the dolomite. In the highly dolomitized sandstones, ghosts and remnants of replaced quartz and feldspar grains (fig. 4 *f*) and volcanic rock fragments are ubiquitous and cannot be accounted for by the minor replacement often accompanying early carbonate cementation. In addition, the presence of quartz overgrowths and occasional pressolved grain contacts similar to those in nondolomitized sandstones, indicate diagenetic modifications were active prior to dolomitization.

Where only moderate to slight dolomitization has occurred, small patches of poikilotopic ferroan dolomite are randomly distributed throughout the rocks (fig. 4 *e*) which are throughly lithified through quartz cementation and mechanical and chemical compaction. Ghosts and remnants of replaced

the irregularly shaped pore (arrow) caused by the dissolution of dolomite that incompletely replaced a feldspar grain (*f*). Pores are impregnated with blue epoxy. San Martino section, sample DF 1121. Plane light. - F. Isolated secondary pore (*sp*) created through the dissolution of ferroan dolomite/ankerite that had an iron oxide coating (arrow). Both the formation of the oxide coating and subsequent dissolution of carbonate are believed to be the result of outcrop weathering. Pores are impregnated with blue epoxy. Danta section, sample CV 3. Plane light.

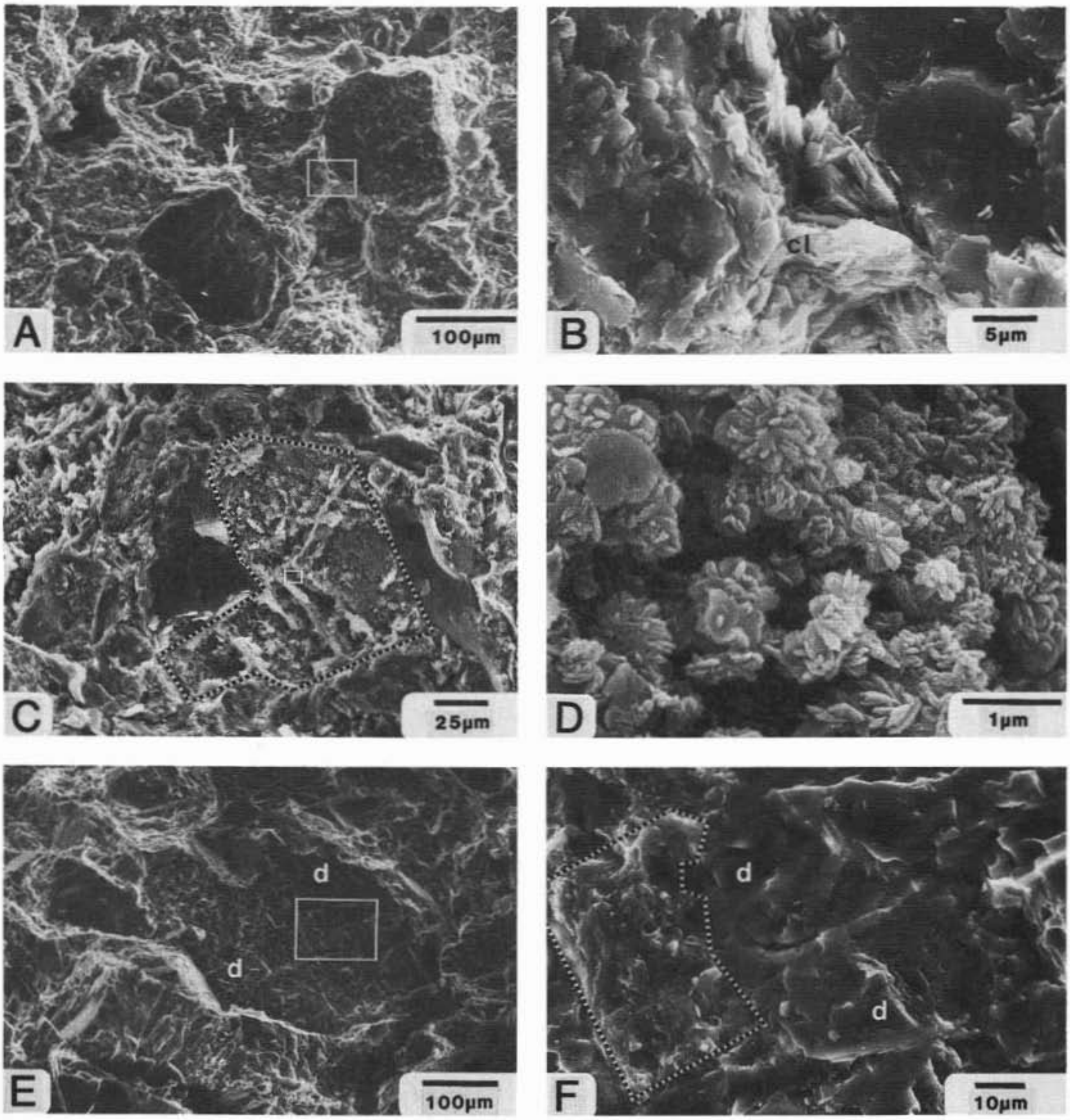

Fig. 6. — Scanning electron micrographs of Val Gardena sandstones from Province A. - A. Intergranular porosity that has been partially occluded by the infiltration of clay matrix (arrows) and subsequently further reduced by mechanical compaction. Paluzza section, sample DF 287. - B. Enlarged view of outlined area in A showing orientation of detrital clay platelets (*cl*) parallel to the surfaces of adjacent framework grains. Compare with figure 4 A. Paluzza section, sample DF 287. - C. Hematite crystals lining void (encircled area) resulting from the dissolution of a chemically unstable framework grain. Danta section, sample CV-5. - D. Enlarged view of outlined area in C showing star-shaped morphology of hematite crystals comprising pore lining. Danta section, sample CV-5. - E. Single crystal of poikilotopic ferroan dolomite (*d*) that is engulfing and partially replacing several framework grains. Compare with figure 4 D. San Martino section, sample DF 1123. - F. Enlarged view of outlined area in E showing framework grain with clay coating (encircled area) partially replaced by poikilotopic ferroan dolomite (*d*). San Martino section, sample DF 1123.

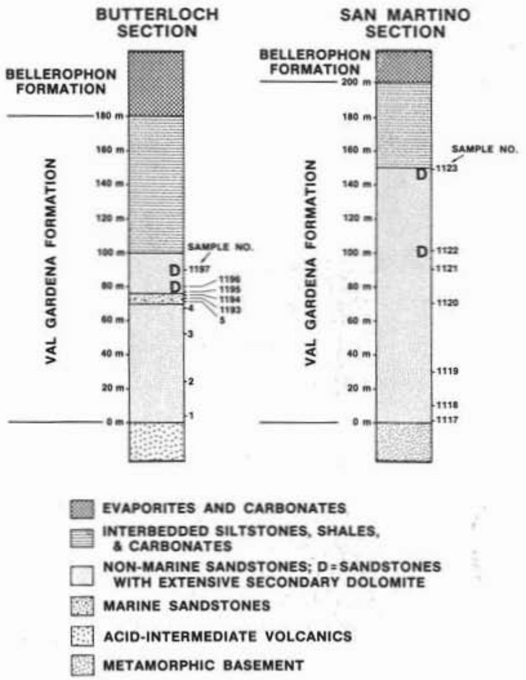

Fig. 7. — Generalized stratigraphic columns for the Butterloch and San Martino sections showing sample distribution and stratigraphic extent of extensive secondary dolomite.

grains are evident but « floating » grains are uncommon due to the small areas dolomitized (fig. 4 *e*).

In the San Martino section where the outcrop samples are accurately located stratigraphically, dolomitization is extensive near the upper contact with the overlying siltstones and shales that cap the Val Gardena Formation and gradually diminishes in extent towards the base of the sandstone (fig. 7, table 1). Although variations in dolomitization of sandstones from the Danta and Paluzza sections are noted, sampling was insufficient and stratigraphic positions of the samples are not accurately enough known to determine the stratigraphic distribution of dolomite.

Mineralization of late fractures, that were probably associated with tectonic activity accompanying uplift, consists of pore-filling ferroan dolomite and barite (fig. 5 *d*). The occurrence of sulfates suggests that fracture-filling proceeded at moderate to shallow depths in the presence of oxygenated meteoric waters (Hawkins, 1978).

There is no primary porosity remaining in the sandstones of Province A, compaction and cementation having produced a tight,

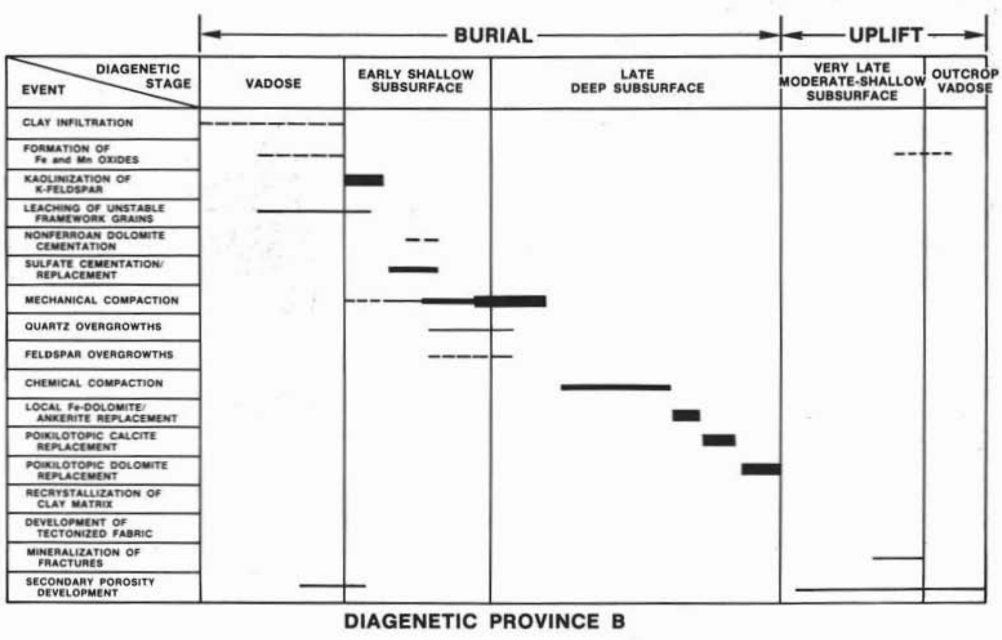

Fig. 8. — General diagenetic stages and events affecting Val Gardena sandstones from Province B. Time increases towards the right; depth increases towards the right until uplift.

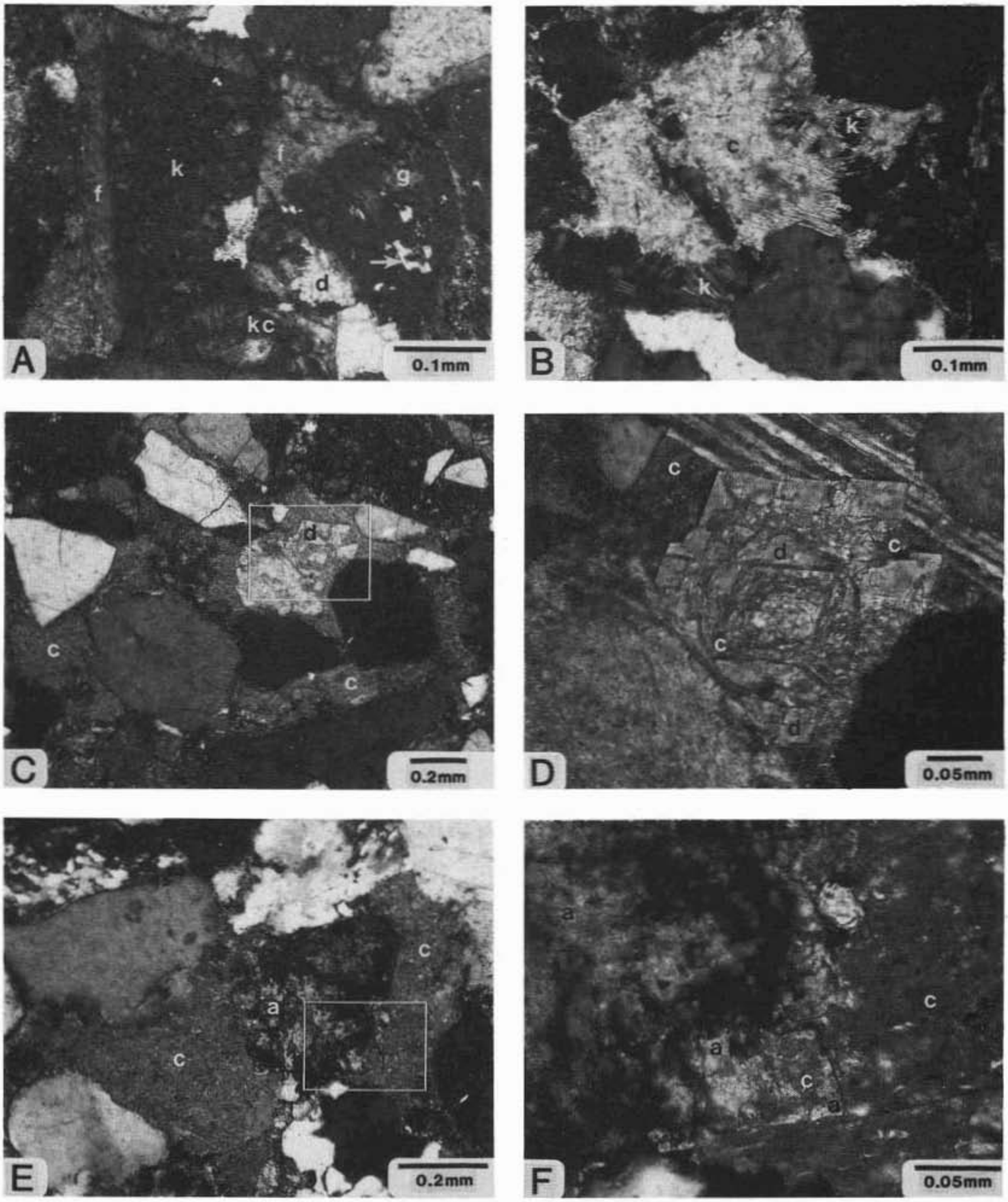

Fig. 9. — Photomicrographs of Val Gardena sandstones from Province B. - A. Detrital potassium feldspars (*f*) that have been replaced by kaolinite (*k*) and gypsum (*g*) that has partially converted to anhydrite (arrow). Intergranular pore is filled by coarsely crystalline kaolinite (*kc*) that has subsequently been partially replaced by dolomite (*d*). Compare with fig. 11 E. Butterloch section, sample DF 1197. Crossed nicols with gypsum plate. - B. Authigenic kaolinite (*k*) engulfed and partially replaced by a later generation of poikilotopic calcite (*c*). Compare with figure 12 C. Butterloch section, sample DF-2. Crossed nicols. - C. Early pore-filling nonferroan dolomite (*d*) cement that is surrounded and partially replaced by poikilotopic calcite (*c*). Dolomite cementation was very localized and is not responsible for substantial porosity reduction. Butterloch section, sample DF-1. Crossed nicols. - D. Enlarged view of outlined area in C showing details of poikilotopic calcite (*c*) replacement

TABLE 1

Semiquantitative X-ray diffraction analysis of bulk Verrucano Lombardo and Val Gardena sandstones

SAMPLE	STRAT. SECTION	QUARTZ	K-FELDSPAR	PLAGIOCLASE	TOTAL CLAYS	CALCITE	DOLOMITE	PYRITE	GYPSUM
DF 188	P	31	-	13	7	1	48	-	-
DF 287	P	52	-	11	28	-	-	9	-
CV 3	D	53	1	25	21	-	-	-	-
CV 4	D	52	-	19	29	-	-	-	-
CV 5	D	34	1	31	34	-	-	-	-
DF 1123	M	16	33	6	6	-	39	-	-
DF 1122	M	23	3	16	6	-	52	-	-
DF 1121	M	66	15	5	11	-	3	-	-
DF 1120	M	57	12	12	18	-	1	-	-
DF 1119	M	48	18	16	18	-	-	-	-
DF 1118	M	53	4	21	21	-	1	-	-
DF 1117	M	65	6	13	15	-	1	-	-
DF 1197	B	29	7	-	-	4	54	-	6
DF 1196	B	45	10	-	8	14	20	-	3
DF 1195	B	41	20	-	12	18	9	-	-
DF 1194	B	18	5	3	7	65	2	-	-
DF 1193	B	32	10	2	10	45	1	-	-
DF 5	B	23	15	-	8	51	3	-	-
DF 4	B	41	20	-	13	19	5	2	-
DF 3	B	48	10	-	14	22	6	-	-
DF 2	B	60	3	-	12	23	2	-	-
DF 1	B	28	5	22	11	26	3	5	-
DF 1150	N	58	10	1	28	-	1	2	-
DF 1149	N	56	9	-	32	-	1	2	-
DF 1148	N	46	11	-	40	-	1	2	-
DF 1144	N	49	9	2	34	-	1	5	-
DF 1154	N	51	14	-	34	-	1	-	-
DF 1153	N	72	7	1	17	-	1	2	-
DF 1143	SG	49	-	2	43	-	-	6	-
DF 1142	SG	56	-	1	36	-	-	7	-
DF 1141	SG	63	-	2	33	-	-	2	-
DF 1140	SG	43	-	2	43	2	4	6	-
DF 1203	SS	49	-	1	46	-	-	4	-
DF 1205	SS	52	-	1	45	-	-	2	-
DF 1206	SS	52	2	1	42	1	-	2	-

Figures are percentages of bulk mineralogy. Key to stratigraphic sections: *P* = Paluzza, *D* = Danta, *M* = San Martino, *B* = Butterloch, *N* = Pizzo della Nebbia, *SG* = Val Sanguigno, *SS* = Val Sassina.

well-lithified rock. Scattered secondary pores created by the dissolution of soluble replacement dolomite (fig. 5 *e*, *f*) (SCHMIDT and MCDONALD, 1979 a, b) are present in some of the sandstones, but never amount to more than a few percent of the bulk rock. The bulk of dissolution is thought to have occurred at moderate to shallow depths while the sandstones were progressively uplifted, but carbonate dissolution on the outcrop cannot be discounted.

Province B

The most distinctive characteristics of sandstones of Province B, and those which serve to distinguish them from rocks of the other provinces, are the presence of both poikilotopic calcite and ferroan dolomite, the lack of common quartz overgrowths, the extensive kaolinization of detrital K-feldspar, and the unrecrystallized nature of the interstitial clay matrix. The complete post-depositional history for these sandstones is: (*a*) localized infiltration of clay matrix shortly after deposition; (*b*) dissolution of chemically unstable framework grains and formation of iron and manganese oxides in the vadose environment; (*c*) extensive kaolinization of detrital K-feldspar; (*d*) sulfate cementation and replacement of K-feldspar; (*e*) localized precipitation of pore-filling nonferroan dolomite; (*f*) formation of quartz and feldspar overgrowths simultaneously with mechanical compaction; (*g*) chemical compaction in the moderate to deep subsurface; (*h*) local replacement by ferroan dolomite/ankerite of detrital grains and matrix; (*i*) massive replacement by poikilotopic calcite; (*j*) late-stage dolomitization; (*k*) creation of secondary porosity through dissolution of carbonates; and (*l*) outcrop weathering (fig. 8).

Unravelling the diagenetic history of the Val Gardena Sandstone from the Butterloch section is complicated by the presence of marine sandstones that interfinger with fluvial sandstones comprising the major portion of the section (fig. 7). For this study, sandstones of the Butterloch section were divided into three informal units: an upper fluvial member, middle marine member, and lower fluvial member. The upper and lower fluvial sandstones respond similarly to changes in the diagenetic environment and, therefore, for the purpose of this study, may be considered as a single unit. The marine sandstones were not studied in detail due to their minor occurrence and are therefore

of nonferroan dolomite (*d*) cement. Note that nonferroan dolomite cement nucleated on detrital grains and subsequently grew into open pore. Butterloch section, sample DF-1. Crossed nicols. - E. Ferroan dolomite/ankerite (*a*) replacement of detrital components that is surrounded and in turn locally replaced by poikilotopic calcite (*c*). Iron oxide alteration of ankerite is a product of outcrop weathering. Compare with figure 12 A. Butterloch section, sample DF 2. Crossed nicols. - F. Enlarged view of outlined area in E showing details of poikilotopic calcite (*c*) replacement of ferroan dolomite/ankerite (*a*). Butterloch section, sample DF-2. Crossed nicols.

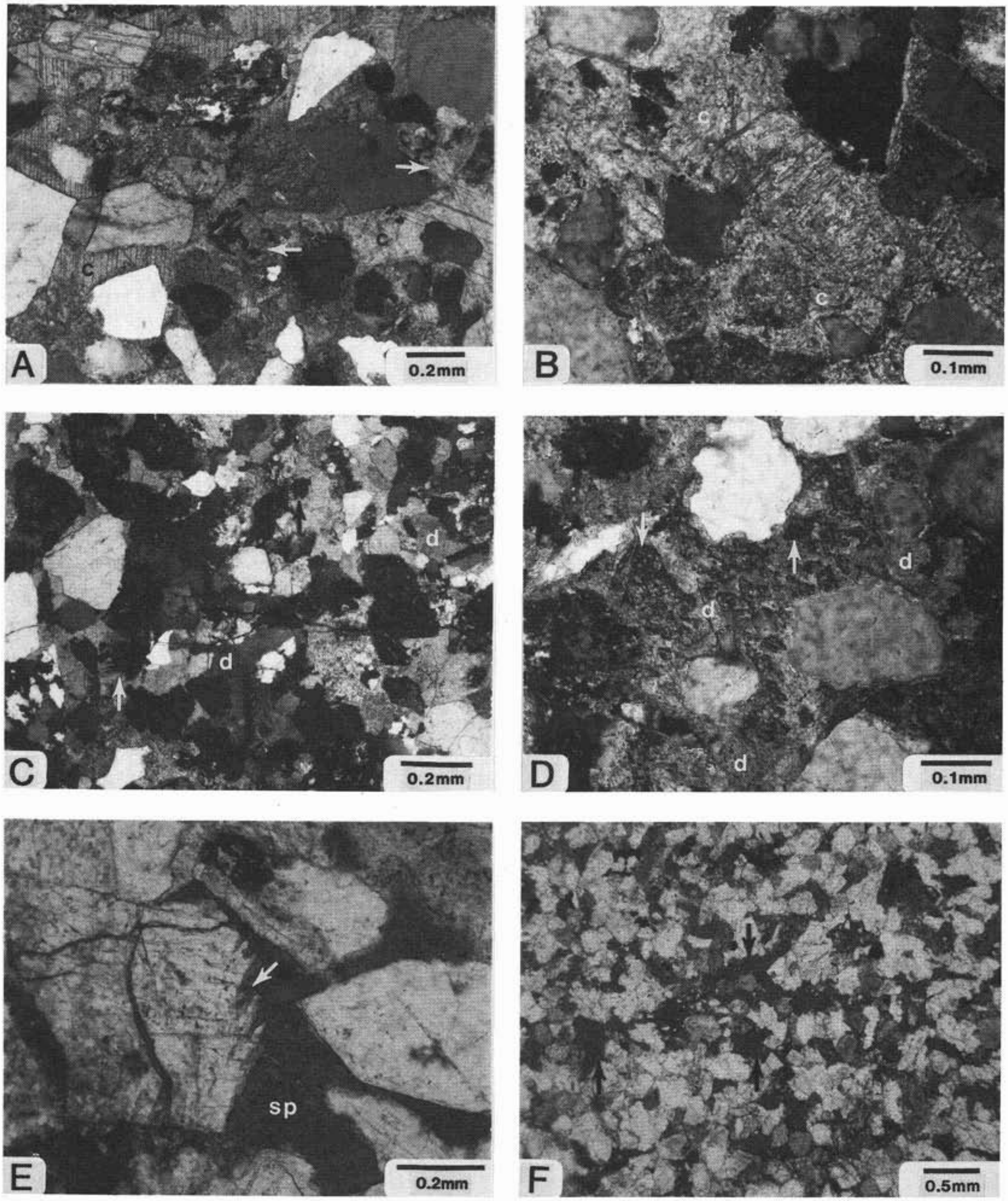

Fig. 10. — Photomicrographs of Val Gardena sandstones from Province B. - A. Detrital grains replaced (arrows) by poikilotopic calcite (*c*). This is the dominant diagenetic feature in the marine sandstones from the Butterloch section. Butterloch section, sample DF 1193. Crossed nicols. - B. Ghost of unknown framework grain that has been replaced by poikilotopic calcite (*c*) in the marine sandstones of the Butterloch section. This suggests the calcite is a late diagenetic component. Butterloch section, sample DF 1193. Crossed nicols. - C. Extensive replacement (arrows) of detrital components by poikilotopic ferroan dolomite (*d*) from near the upper contact of the Val Gardena sandstone. Butterloch section, sample DF 1197. Crossed nicols with gypsum plate. - D. Syntaxial replacement of poikilotopic calcite (arrows) by later generation of poikilotopic ferroan dolomite (*d*). Calcite has been stained with Alizarin Red S. Butterloch section, sample DF 1196. Crossed nicols. -

not emphasized in the following discussion.

The early post-depositional to shallow subsurface history of the Val Gardena sandstones of Province B is similar to that documented for sandstones of Province A. This includes the early post-depositional infiltration of clay, reddening of framework grains and clay matrix due to the formation of iron and manganese oxides (fig. 11 *a, b*), and the simultaneous nucleation of quartz overgrowths (fig. 11 *c*) and porosity destruction by mechanical compaction. Four additional early cements, kaolinite, nonferroan dolomite, gypsum, and minor anhydrite, serve to distinguish sandstones of Province B from those previously described.

Sandstones from the Butterloch section are distinguished by a high K-feldspar/plagioclase ratio relative to the other rocks studied. In the shallow subsurface environment these K-feldspars and rhyolitic volcanic fragments, which consist largely of K-feldspar, are readily altered to kaolinite (figs. 9 *a*, 11 *e*) in the presence of acid meteoric waters (HANCOCK and TAYLOR, 1978). Where replacement of feldspar is particularly extensive, kaolinite also occurs as localized pore-fillings (fig. 9 *a*). The abundance of kaolinite is important because of the large volume of microporosity between the clay platelets. In most cases, microporosity is not effective porosity due to the small pore throat diameter which restricts fluid flow (PITTMAN, 1979).

In addition to kaolinite, many of the detrital K-feldspars are partially replaced by gypsum (figs. 9 *a*; 11 *e, f*), and to a lesser extent by anhydrite. Textural relationships indicate that kaolinite formed prior to the sulfates (fig. 11 *f*), and although both are believed to have formed in the early subsurface diagenetic environment, the absolute timing of events is uncertain. It is possible that the calcium-enriched hypersaline waters necessary for the precipitation of gypsum are the same waters responsible for the formation of the overlying Bellerophon evaporites. Upon moderate to deep burial, the elevated temperatures and pressures resulted in the gradual conversion of gypsum to anhydrite. Either burial was too shallow for the complete conversion of gypsum to anhydrite, or the gypsum presently in these rocks is the product of extensive outcrop rehydration of anhydrite.

Nonferroan dolomite is present as an early pore-filling cement in a few sandstones from the base of the Butterloch section. It consists of rhombic crystals that nucleated on framework grains and subsequently grew unrestricted into open pores (fig. 9 *c, d*), implying cementation occurred before mechanical and chemical compaction had completely occluded porosity. Although this cement is nonferroan, energy dispersive X-ray anaylsis indicates that minor manganese substitution is common. Poikilotopic calcite invariability engulfs the nonferroan dolomite cement and often partially replaces it (fig. 9 *d*), thereby establishing the paragenetic relationship between these two carbonates. Due to its limited occurrence, this pore-filling dolomite is not a major contributor to porosity reduction in the sandstones of Province B.

After destruction of almost all remaining primary porosity by further mechanical and chemical compaction, the sandstones were subjected to a relatively minor episode of patchy ferroan dolomite/ankerite replacement. The replacement consists of single or multiple, occasionally rhombic, crystals (figs. 9*e*; 12*a*) that are disseminated throughout the rock. Commonly, they contain inclusions of iron oxide which form peripheral zones in the crystals (figs. 9 *f*; 12 *b*). Remnants of partially replaced framework grains or clay matrix are sometimes visible within the dolomite, but this relationships is not commonly observed, probably due to its patchy distribution. Because of the oxide inclusions and their subhedral to anhedral outline, these dolomites were initially interpreted to be detrital carbonate rock fragments. The lack of any obvious dolomite source terrane and the subtle replacement textures leads to

E. Secondary intergranular porosity (*sp*) created through dissolution of authigenic carbonates. Etched feldspar (arrow) is the result of partial replacement by authigenic carbonate. Pores are impregnated with blue epoxy. Butterloch section, sample DF-2. Plane light. - F. Secondary pores (arrows) created through the dissolution of large crystals of poikilotopic carbonate. Although porosity is locally abundant on a microscopic scale, it is not pervasive throughout the rock. Butterloch section, sample DF-3. Plane light.

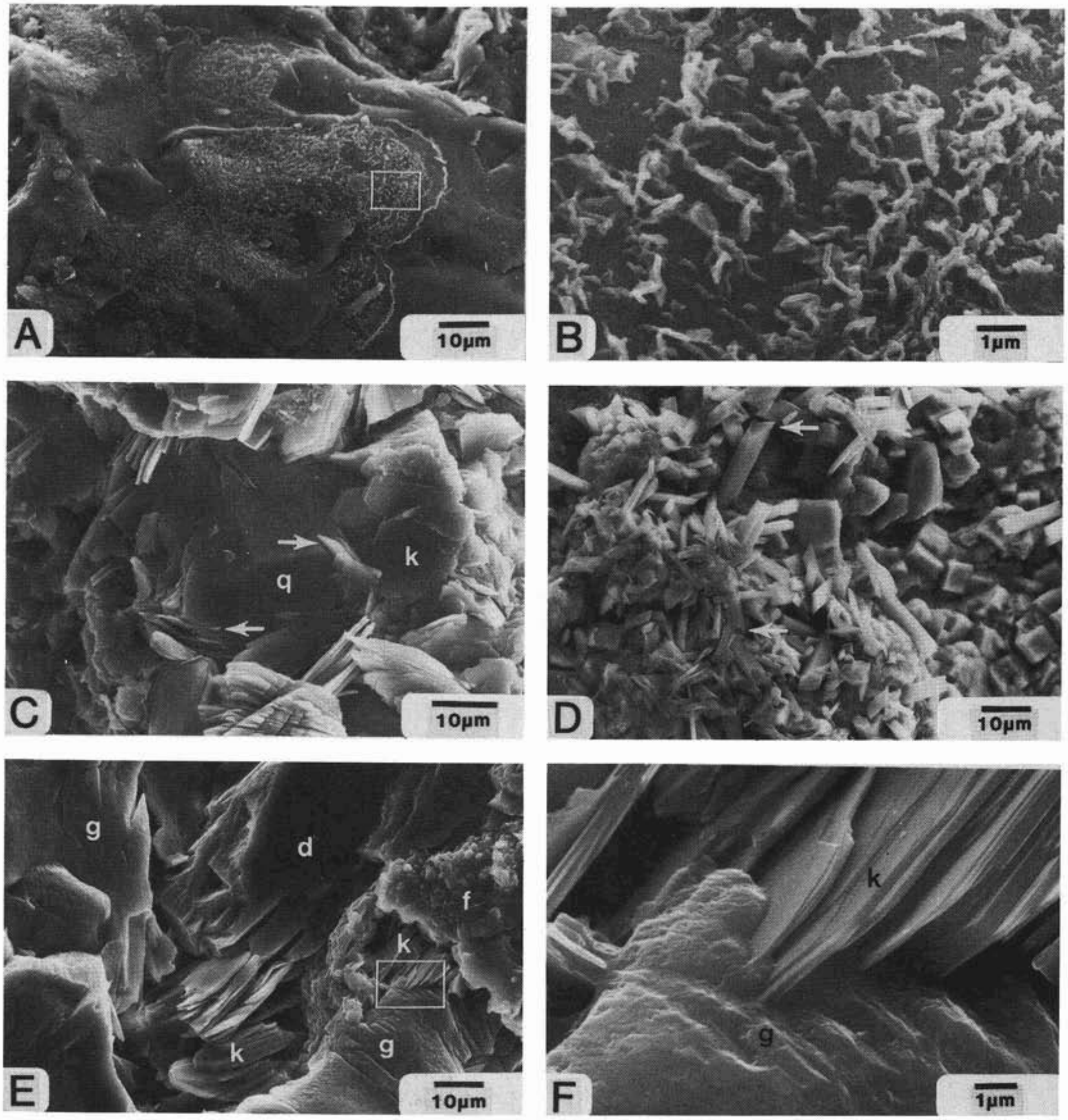

Fig. 11. — Scanning electron micrographs of Val Gardena sandstones from Province B. - A. Manganese oxide (pyrolusite?) coating on the surface of detrital quartz grain. Butterloch section, sample DF 1195. - B. Enlarged view of outlined area in A showing anastomosing morphology of the manganese oxide crystals. Butterloch section, sample DF 1195. - C. Quartz overgrowth (*q*) filling pore that is lined by authigenic kaolinite (*k*). Growth of quartz around previously formed kaolinite (arrows) establishes paragenetic sequence of the two minerals. Butterloch section, sample DF-3. - D. Gypsum crystals filling late fracture that is probably a result of tectonism accompanying uplift. Note characteristic « shallow-tail » twinning of gypsum (arrows). Butterloch section, sample DF 1197. - E. Detrital potassium feldspar (*f*) partially replaced by kaolinite (*k*) which has in turn been engulfed by gypsum (*g*). Poikilotopic ferroan dolomite (*d*) has engulfed pore-filling kaolinite. Compare with figure 9 A. Butterloch section, sample DF 1197. - F. Enlarged view of outlined area in E showing kaolinite (*k*) replacement of potassium feldspar engulfed by gypsum (*g*). Butterloch section, sample DF 1197.

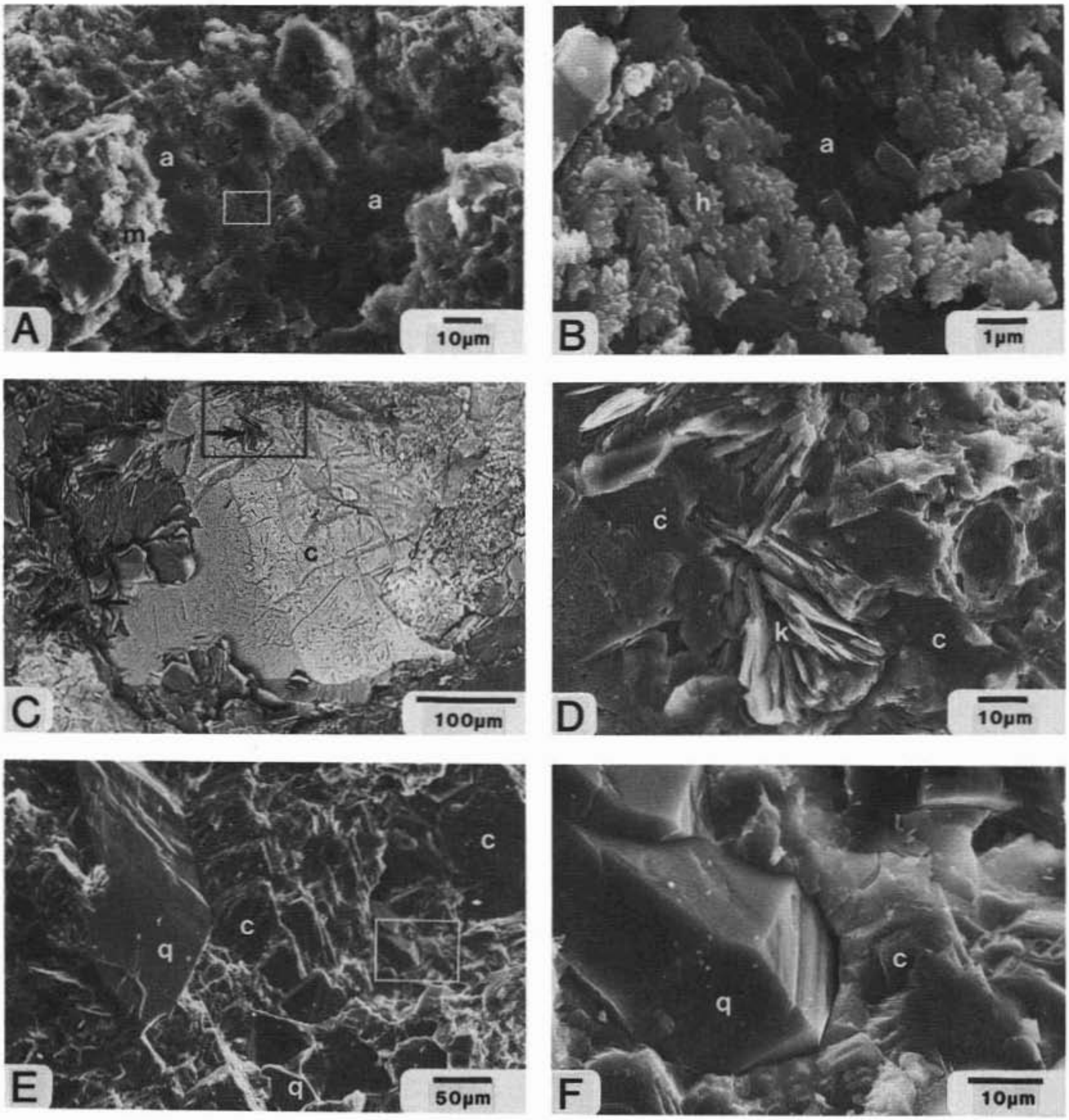

Fig. 12. — Scanning electron micrographs of Val Gardena sandstones from Province B. - A. Ferroan dolomite/ankerite (*a*) that has replaced detrital grains and matrix (*m*). Note sparse coating of iron oxide on ferroan dolomite and the small dissolution voids in ferroan dolomite. Compare with figure 9 E. Butterloch section, sample DF 1195. - B. Enlarged view of outlined area in A showing star-shaped hematite (*h*) crystals coating ferroan dolomite/ankerite (*a*). This hematite, which is probably a result of outcrop weathering, is similar to that associated with dissolved framework grains (see fig. 6 D). Butterloch section, sample DF 1195. - C. Pore-filling kaolinite (arrows) engulfed by large crystal of poikilotopic calcite (*c*). Compare with figure 9 B. Butterloch section, sample DF-2. Backscattered electron image. - D. Enlarged view of outlined area in C showing details of kaolinite (*k*) engulfed by poikilotopic calcite (*c*). This relationship establishes the paragenetic sequence of these two minerals. Butterloch section, samples DF-2. - E. Poikilotopic calcite (*c*) that has formed after an earlier period of silica cementation as represented by quartz overgrowths (*q*). Butterloch section, sample DF-2. - F. Enlarged view of outlined area in E showing poikilotopic calcite (*c*) surrounding quartz overgrowth (*q*). This relationship establishes the paragenetic sequence of these two minerals. Butterloch section, sample DF-2.

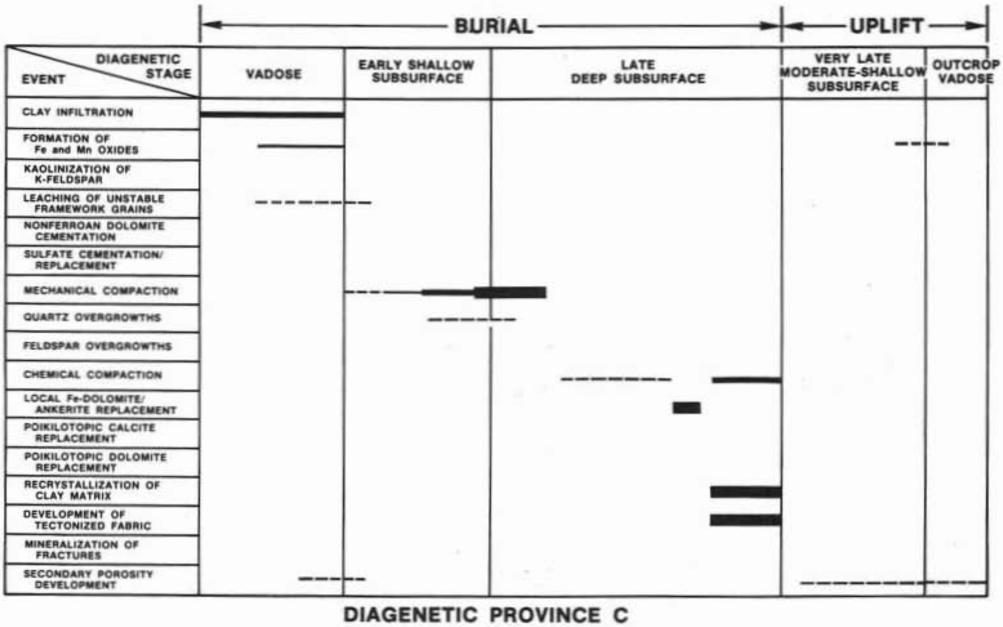

Fig. 13. — General diagenetic stages and events affecting Verrucano Lombardo sandstones from Province C. Time increases towards the right; depth increases towards the right until uplift.

their reinterpretation as authigenic carbonates. The oxide inclusions are probably a product of surficial outcrop weathering resulting from the relatively large amount of iron substitution in the dolomite. This patchy replacement dolomite/ankerite is present to some degree in all the nonmarine sandstones, but is most noticeable in the lower fluvial sandstones where it has not been replaced by later calcite or ferroan dolomite. This is evident in the X-ray diffraction data (table 1) which shows the lower fluvial sandstones to contain 2-6 percent dolomite which has been determined petrographically to be patchy ferroan dolomite/ankerite. In the upper fluvial sandstones remnants of the patchy dolomite are visible in large crystals of poikilotopic calcite (fig. 9 *f*) and/or poikilotopic ferroan dolomite attesting to their earlier formation.

After the episode of minor ferroan dolomite/ankerite replacement, the sandstones of Province B were subjected to two separate periods of pervasive late-stage carbonate replacement. Calcite is present throughout the entire Butterloch section, but is more abundant in the marine facies where it can amount to over 60 percent (weight percent based on XRD) of the rock (table 1). Among the nonmarine sandstones calcite is more abundant (19-26 percent) in the lower part of the Val Gardena Sandstone and becomes progressively less abundant (4 percent) towards the upper contact with the overlying siltstones and shales (table 1). It is usually poikilotopic with individual crystals up to 2 mm in length. Textural relationships indicate that calcite formed after kaolinite replacement of feldspars (figs. 9 *b*; 12 *c, d*), quartz overgrowths (fig. 12 *e, f*), and patchy ferroan dolomite/ankerite replacement (fig. 9 *e, f*), but before the poikilotopic ferroan dolomite. Ghosts and remnants of replaced framework grains are evident in the calcite, particularly in the marine facies where replacement is extensive (fig. 10 *a, b*).

Poikilotopic ferroan dolomite is present in sandstones of Province B as a late-stage replacement of the poikilotopic calcite. This late ferroan dolomite is restricted to the upper part of the Val Gardena Sandstone, particularly to the upper nonmarine facies. Dolomitization is extensive near the upper contact with the overlying siltstones and shales that cap the Val Gardena Formation (figs. 7, 10 *c*), and progressively decreases towards the interfingering marine facies where there is little evidence of dolomitization (table 1). This trend of decreasing dolomitization away from the upper sandstone contact is similar to that exhibited by sandstones from the San Martino section of Province A. Near the upper contact where dolomitization is most extensive no remnants of the replaced poikilotopic calcite are evident petrographically, although X-ray diffraction data indicate that a small amount of calcite is present in the bulk sample (table 1). Near the contact between the upper nonmarine facies and the underlying marine sandstones remnant patches of poikilotopic calcite are more numerous and are syntaxially replaced by poikilotopic ferroan dolomite (fig. 10 *d*). Although sampling is sparse, there appears to be a direct correlation between the decrease in dolomitization away from the upper contact and an increase in the amount of remnant poikilotopic calcite. Remnants of the earlier ferroan dolomite/ankerite replacement are visible within the poikilotopic ferroan dolomite by virtue of their characteristic iron oxide inclusions and rims.

Gypsum occurs as a mineralization of late fractures (fig. 11 *d*) that were probably associated with tectonism accompanying uplift. Although no ferroan dolomite or barite fills these fractures, as is the case for fractures in the sandstones of Province A, all the fractures probably formed at the same time with local variations in ground water chemistry being responsible for the differences in fracture fillings. The presence of gypsum instead of anhydrite suggests the mineralization occurred at moderate to shallow depths.

Primary porosity in the sandstones of Province B has been completely destroyed by compaction and cementation, although dissolution of both calcite and dolomite has created patchy secondary porosity (fig. 10 *e*) in some of the rocks. Because this porosity is generated primarily through the removal of late-stage authigenic minerals, it must necessarily have formed very late in the diagenetic history of the sandstones. Most of the dissolution is throught to have occurred in the moderate to shallow subsurface in the presence of acidic meteoric waters that flushed the sandstones during uplift. Some of the secondary porosity, particularly that created through the dissolution of the patchy ferroan dolomite/ankerite replacement, is interpreted to have taken place at the surface as a result of outcrop weathering. As previously discussed, the iron oxides which form peripheral zones in these carbonates are probably the product of surficial weathering. Where dissolution of this ferroan dolomite/ankerite is complete, the iron oxides are left unaffected as linings of the newly created pores.

The majority of the secondary pores generated in this manner are generally isolated and do little to increase the overall porosity and permeability of the rocks. Occasionally large poikilotopic crystals of calcite or ferroan dolomite are dissolved creating domains a few millimeters to a centimeter in diameter of relatively high porosity (fig. 10 *f*). Despite these local areas of increased porosity, the overall porosity of the rocks remains low due to the irregular distribution of the pores.

Province C

The distinguishing characteristics of sandstones of Province C are the lack of late-stage carbonate replacement, quartz overgrowths, and authigenic kaolinite, and the high degree of recrystallization of the clay matrix. The complete diagenetic history of these sandstones is: (*a*) extensive infiltration of clay matrix shortly after deposition; (*b*) formation of iron oxide in the shallow subsurface environment; (*c*) minor quartz cementation concurrent with extensive mechanical compaction; (*d*) minor chemical compaction; (*e*) localized replacement by ferroan dolomite/ankerite; (*f*) extensive recrystallization of clay matrix and iron oxides, and deformation of framework grains; (*g*) development of minor secondary porosity; and (*h*) outcrop weathering (fig. 13).

The early diagenetic history of Province C sandstones is similar to that of sandstones of Provinces A and B with a few exceptions. Infiltration of clay matrix was more extensive in these sandstones as is evident by their more argillaceous composition (table 1). Formation of iron oxides in the vadose environment proceeded in a manner similar to the

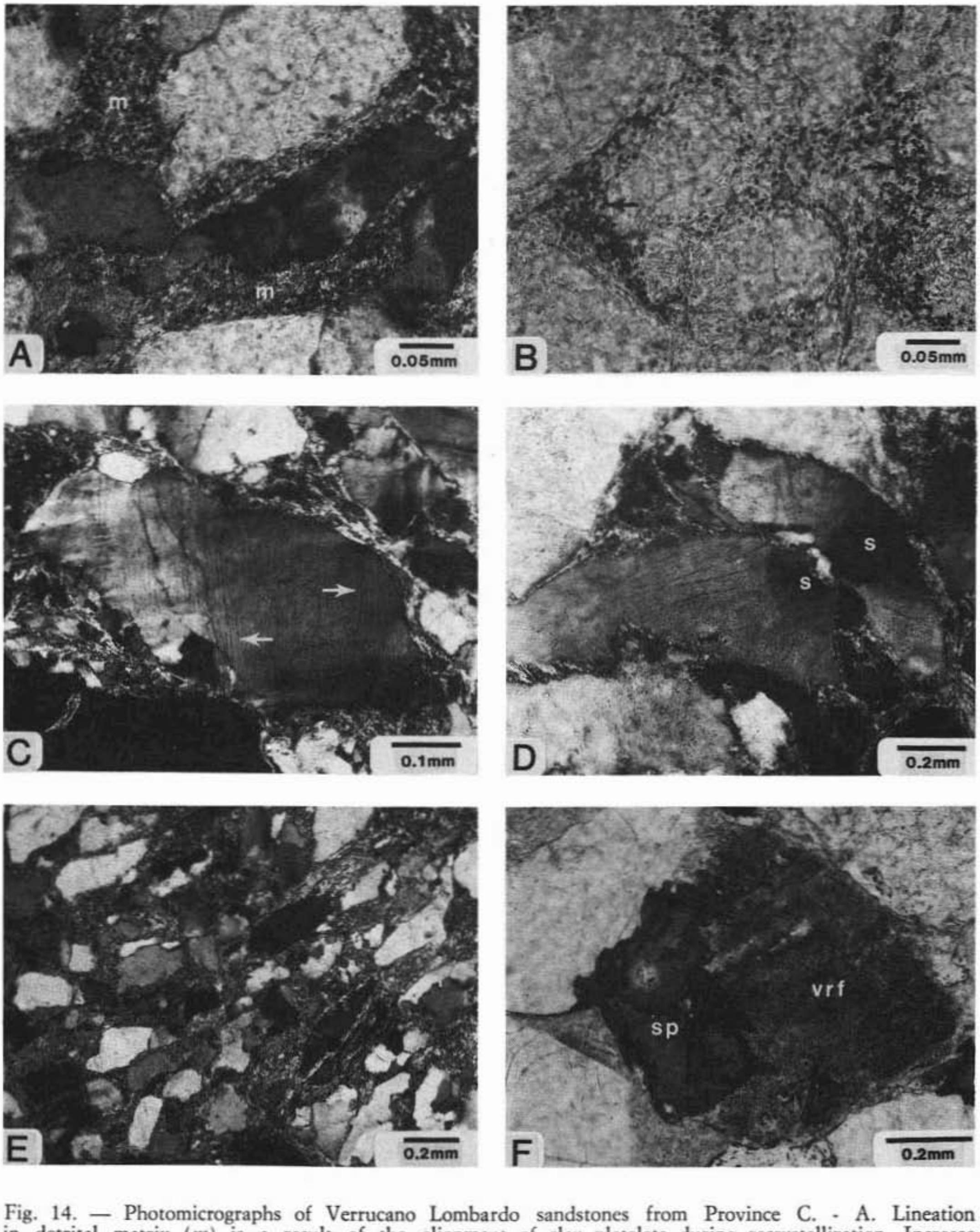

Fig. 14. — Photomicrographs of Verrucano Lombardo sandstones from Province C. - A. Lineation in detrital matrix (*m*) is a result of the alignment of clay platelets during recrystallization. Increase in size and apparent birefringence of clay platelets are also a result of recrystallization. Compare with figure 15 A. Val Sassina section, sample DF 1205. Crossed nicols. - B. Small crystals of hematite (arrows) aligned parallel to clay platelets are a product of the recrystallization of amorphous iron stain that coated the clay matrix prior to recrystallization. Val Sassina section, sample DF 1205. Plane light. - C. Boehm lamellae (arrows) in strongly deformed quartz grain. The presence of these deformation features only in sandstones of Province C suggest they formed *in situ*. Pizzo della Nebbia section, sample 1150. Crossed nicols. - D. Interpenetration of two detrital quartz grains with strain shadows (*s*) in both grains coincident with point of contact. This clearly demonstrates that the deformation oc-

other sandstones and is assumed to have developed as an intense stain on the detrital clay. Only minor quartz cementation and chemical compaction (pressure solution) have affected these rocks, presumably a result of the abundant clay matrix which prevented quartz cementation by restricting nucleation sites, and inhibited pressure solution by reducing the number of grain-to-grain contacts. Mechanical compaction is the main agent of porosity reduction in these sandstones as indicated by the common occurrence of highly deformed detrital micas and fractured feldspars, and the general lack of authigenic cements. Minor patchy ferroan dolomite/ankerite (fig. 15 *e*) replacement after compaction is evident in some of the sandstones, but is not common enough to be considered characteristic of this province.

The single most distinctive characteristic of Province C sandstones is the highly recrystallized state of the clay matrix and associated iron oxide stain. The recrystallization is indicated petrographically by the increased size and apparent birefringence of the clay platelets and by an obvious lineation resulting from an alignment of the platelets (figs. 14 *a*; 15 *a, b*). Argillaceous sedimentary rock fragments are also recrystallized and, in some cases, are difficult to distinguish from interstitial matrix. Recrystallization is also apparent from the X-ray diffraction data as indicated by the relative sharpness of the 10 Å illite reflection (WEAVER, 1960). The average illite sharpness ratios for sandstones of Provinces A and B are 2.6 and 2.0, respectively (table 2). By comparison with sharpness ratios in rocks from the Quachita structural belt of Texas and Oklahoma (WEAVER, 1961), these low values indicate the rocks have not undergone any meta morphism. The average illite sharpness ratio for sandstones of Province C is 7.1, which by comparison indicates very weak to weak metamorphism of the rocks (WEAVER, 1961). Despite recrystallization the mineralogic composition of the illitic clay comprising the matrix has remained essentially unchanged. Illitic clays in sandstones of Provinces A and B have an average of 92 percent illite interlayers (expandable clays comprising the remainder), compared to an average of 96 percent illite interlayers in the clays of Province C sandstones (table 2).

TABLE 2

Semiquantitative X-ray diffraction analysis of < 2 micrometer size fraction of Verrucano Lombardo and Val Gardena sandstones

SAMPLE	STRAT. SECTION	ILLITE	KAOLINITE	CHLORITE	QUARTZ	TOTAL FELDSPARS	CALCITE	DOLOMITE	ILLITE SHARPNESS RATIO	ILLITE COMPOSITION
DF 188	P	55	-	-	19	9	-	17	3.1	93
DF 287	P	75	-	9	13	3	-	-	4.1	97
CV 3	D	63	-	-	25	12	-	-	3.0	93
CV 4	D	74	-	-	18	8	-	-	2.7	96
CV 5	D	92	-	-	5	3	-	-	2.2	95
DF 1123	M	28	4	3	16	9	-	40	2.8	90
DF 1122	M	37	13	3	15	7	-	25	2.0	93
DF 1121	M	47	15	3	26	5	-	4	1.8	92
DF 1120	M	69	5	8	14	4	-	-	2.1	93
DF 1119	M	77	2	3	15	3	-	-	2.1	97
DF 1118	M	85	1	2	10	2	-	-	2.4	90
DF 1117	M	35	-	2	19	44	-	-	2.3	91
DF 1197	B	7	31	-	24	7	-	31	-	93
DF 1196	B	15	35	-	28	7	4	11	2.0	93
DF 1195	B	22	42	-	20	4	3	9	2.0	94
DF 1194	B	21	22	-	7	1	45	4	1.6	93
DF 1193	B	20	45	-	9	2	23	1	2.1	94
DF 5	B	13	41	-	15	4	24	3	1.6	95
DF 4	B	25	51	-	10	4	6	4	2.4	92
DF 3	B	36	34	-	12	4	10	4	2.3	89
DF 2	B	32	32	-	18	4	11	3	1.9	90
DF 1	B	59	16	-	14	5	4	2	2.0	85
DF 1150	N	78	-	-	18	3	-	1	8.4	97
DF 1149	N	78	-	-	20	2	-	-	7.6	98
DF 1148	N	79	-	-	17	3	-	1	8.7	96
DF 1144	N	75	-	-	17	4	3	1	9.4	97
DF 1154	N	76	-	-	19	4	-	1	6.7	96
DF 1153	N	61	-	-	34	4	-	1	7.6	96
DF 1143	SG	97	-	-	2	1	-	-	7.0	96
DF 1142	SG	93	-	-	6	1	-	-	5.1	95
DF 1141	SG	93	-	-	6	1	-	-	7.9	96
DF 1140	SG	89	-	-	10	1	-	-	8.6	95
DF 1203	SS	99	-	-	1	-	-	-	4.9	95
DF 1205	SS	98	-	-	2	-	-	-	4.4	95
DF 1206	SS	97	-	-	3	-	-	-	5.8	97

Figures are percentages of clay-size mineralogy. For key to stratigraphic sections see Table 1.

Associated with the recrystallized matrix are small, sometimes euhedral, hematite crystals that are aligned parallel to the lineation of the clay platelets (fig. 14 *b*). The size and orientation of this crystalline hematite is additional evidence for extensive recrystallization of the argillaceous com-

curred *in situ*. Pizzo della Nebbia, sample 1153. Crossed nicols. - E. Alignment of elongate framework grains as a result of high tectonic stress imparts a foliate fabric to the rock. This texture is similar to that exhibited by upper textural zone 1 and lower textural zone 2 metagraywackes of the circumpacific region. Compare with figure 15 C. Val Sassina section, sample DF 1205. Crossed nicols with gypsum plate. - F. Secondary pore (*sp*) created through dissolution of ferroan dolomite/ankerite that had partially replaced a volcanic rock fragment (*vrf*). This is the only type of porosity in sandstones of Province C. Pore is impregnated with blue epoxy. Compare with figure 15 F. Val Sanguigno section, sample 1141. Plane light.

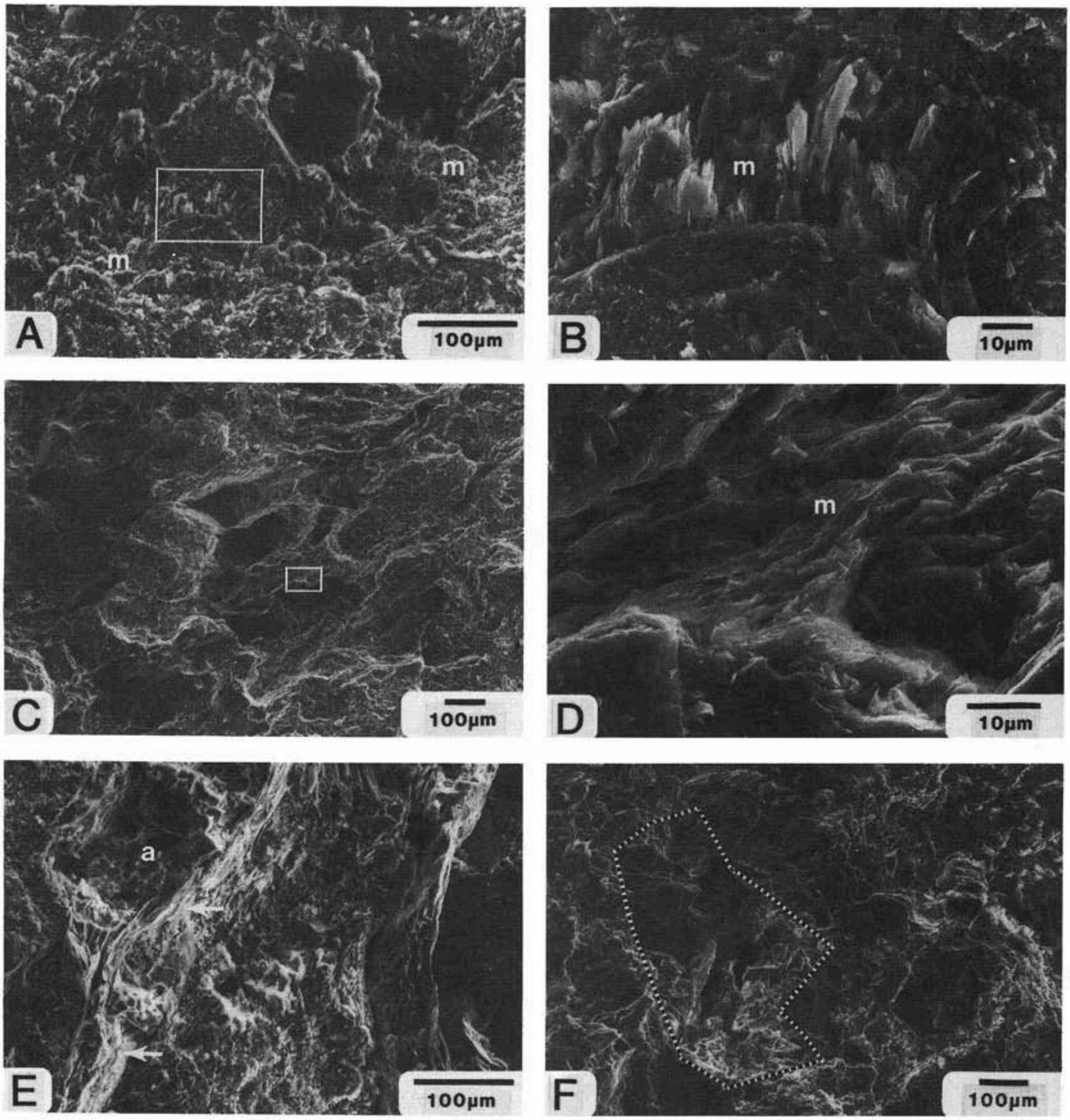

Fig. 15. — Scanning electron micrographs of Verrucano Lombardo sandstones from Province C. - A. Abundant recrystallized clay matrix (*m*) effectively occludes intergranular porosity. Clay matrix is most abundant in sandstones of Province C. Compare with figure 14 A. Pizzo della Nebbia section, sample DF 1144. - B. Enlarged view of outlined area in A showing coarse clay platelets that are characteristic of the recrystallized matrix (*m*). Pizzo della Nebbia section, sample DF 1144. - C. Foliate fabric resulting from the alignment of elongate framework grains due to tectonic stress. Compare with figure 14 E. Val Sassina section, sample DF 1205. - D. Enlarged view of outlined area in C showing alignment of recrystallized matrix (*m*) parallel to framework grains. Val Sassina section, sample DF 1205. - E. Ferroan dolomite/ankerite (*a*) replacement of detrital components. Deviation of matrix (arrows) around ferroan dolomite indicates replacement occurred before recrystallization of matrix. Val Sanguigno section, sample DF 1140. - F. Secondary pore (encircled area) left by the dissolution of ferroan dolomite/ankerite similar to that in E. This type of isolated secondary porosity is the only porosity in sandstones of Province C. Compare with figure 14 F. Val Sanguigno section, sample DF 1141.

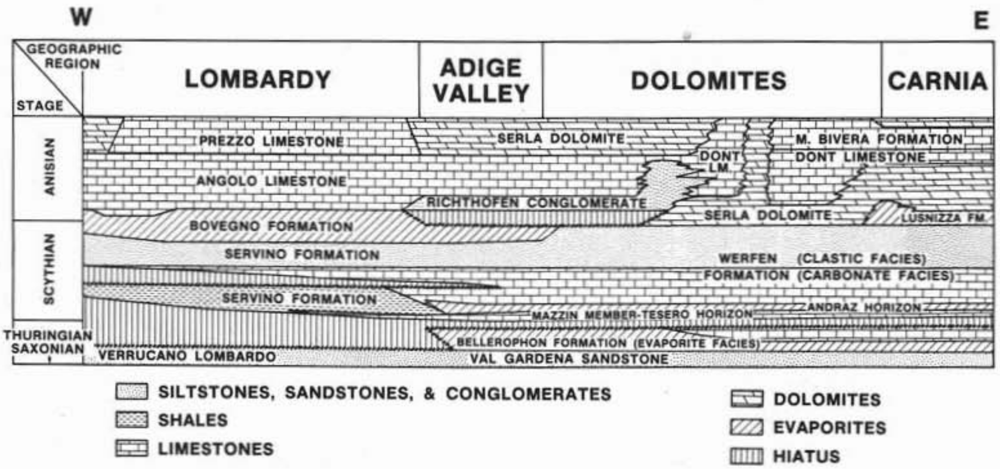

Fig. 16. — Generalized profile across northern Italy showing lithologies of the Upper Permian and Lower Triassic strata. (Modified from CASSINIS et al., 1979 and ASSERETO et al., 1973).

ponents of these rocks. These crystals are thought to be the product of recrystallization of the iron oxide stain that originally coated the interstitial clay matrix.

These rocks exhibit other signs of incipient metamorphism, including strong undulatory extinction of quartz (fig. 14 *d*), the presence of Boehm lamellae in strongly deformed quartz grains (fig. 14 *c*), and fractures radiating away from the contacts of framework grains. Texturally, these sandstones (figs. 14 *e*; 15 *c, d*) are similar to the upper textural zone 1 and lower textural zone 2 metagraywackes from the blueschist facies of the Franciscan Formation of California (BLAKE et al., 1967), and similar metagraywackes of the greenschist facies of the Otago area of New Zealand (REED, 1958). Despite the development of microscopic deformation features, and the micaceous nature of these sandstones, there is no indication of the platy rock cleavage, as seen under a hand lens, that is characteristic of sandstones of textural zone 2 (BLAKE et al., 1967). These deformation features and the recrystallization of the clay matrix are possibly the result of structural deformation related to the late Cretaceous-Tertiary continental collision (MILNES, 1978) which affected the sandstones of Province C to a greater extent than those of Provinces A and B.

As a group, the sandstones of Province C have the lowest porosity of any of the three provinces. Not only is all primary porosity destroyed by compaction and cementation, but minor secondary porosity is present in only a few of the sandstones. Secondary pores are created through the dissolution of widely scattered patches of ferroan dolomite/ankerite (figs. 14 *f*; 15 *f*) and consequently do not form an effective pore network.

Origin of carbonates

An important relationship between poikilotopic ferroan dolomite and calcite is elucidated in sandstones of the Butterloch section. Petrographic evidence from these rocks clearly demonstrates that poikilotopic ferroan dolomite is a replacement of an earlier generation of poikilotopic calcite with which it is usually in optical continuity. In the San Martino section, where dolomitization is also extensive, there is no indication from either petrographic or X-ray diffraction data of the presence or former existence of calcite. It is possible that poikilotopic calcite was at one time common in these sandstones and has since been completely replaced by ferroan dolomite. If this is indeed the case, it suggests that a poikilotopic calcite precursor may be necessary for extensive poikilotopic ferroan dolomitization to occur.

In both the San Martino section of Province A and Butterloch section of Province B, where the stratigraphic positions of the samples are accurately known, the zone of extensive dolomitization is restricted to the upper part of the sandstones comprising the Val Gardena Formation (fig. 7). In the Butterloch section this zone is at least 10 m thick, while in the San Martino section, where the sample density is less, the zone may be as thick as 50 m. Due to the lack of samples from the siltstones and shales that comprise the upper 50-80 meters of the Val Gardena Formation the exact thickness of the dolomitized zone is unknown and may be greater than indicated above.

It is noteworthy that this zone is present in the Val Gardena sandstones of Provinces A and B, but appears to be absent from the sandstones of Province C. In the Dolomites and Carnia regions (Provinces A and B) the Val Gardena Sandstone is overlain by carbonates and evaporites of the Permian Bellerophon Formation, which are in turn overlain by carbonate and clastic facies of the Lower Triassic Werfen Formation (fig. 16). The Middle Triassic section consists dominantly of carbonates which have been affected by extensive regional dolomitization. To the west in the Lombardy region (Province C), where the evaporites of the Bellerophon Formation were either never deposited or were subsequently eroded, the Verrucano Lombardo Sandstone is directly overlain by the clastic facies of the Lower Triassic Servino Formation. In this region the Middle Triassic carbonate section has not been greatly affected by regional dolomitization (fig. 16).

During Thuringian (Late Permian) time when evaporites were forming on top of the shallow buried Val Gardena sediments (fig. 16), hypersaline conditions are presumed to have existed with brines having salinity in excess of 35 ‰ and Mg^{+2}/Ca^{+2} ratio in excess of 3:1 (FOLK, 1974 a, b). With the precipitation of gypsum acting as a sink for Ca^{+2}, the Mg^{+2}/Ca^{+2} ratio would increase to the point where dolomite would begin to precipitate from solution. At this point migration of these brines into the underlying poorly to moderately consolidated clastic sediments would result in the formation of early pore-filling dolomite cement. This type of early cement has indeed been observed in some of the Val Gardena Sandstones from the Butterloch section as scattered rhombs of nonferroan dolomite attached to adjacent framework grains (fig. 9 *c, d*).

Formation of the poikilotopic ferroan dolomite (fig. 10 *c*) and its calcite precursor (fig. 10 *d*) occurred late in the diagenetic history of the sandstones and, therefore, is probably not related to the directly overlying Bellerophon evaporites. The poikilotopic calcite may instead have been derived from waters related to the formation of the overlying Middle Triassic (Anisian) carbonate sequence, with extensive calcite replacement of framework grains being restricted to those sandstones with little to moderate clay matrix. Sandstones of Provinces A and B, therefore, have been extensively replaced by poikilotopic calcite, while those of Province C which contain substantial clay matrix have not been affected by late-stage carbonate replacement.

The replacement of poikilotopic calcite by poikilotopic ferroan dolomite (fig. 10 *d*) may, in turn, be related to the regional dolomitization which affected the Middle Triassic (Anisian) carbonate sequence of Provinces A and B (Dolomites and Carnia regions of fig. 16). If this is the case, dolomitization is controlled, in part, by basinal hydrology in the overlying Triassic section shortly before or during uplift when large scale flushing by meteoric waters was initiated.

Origin of porosity

Only residual primary porosity remains in the Verrucano Lombardo and Val Gardena Sandstones due to extensive porosity destruction by mechanical and chemical compaction as well as quartz cementation and carbonate replacement. In those sandstones that lack significant carbonate components, the destruction of primary porosity signals the termination of the rocks as effective fluid pathways. All the sandstones from Province C examined in this study fall into this category. Those sandstones that contain substantial carbonate, either in the form of early pore-filling cement or late-stage replacement, are susceptible to subsurface dissolution resulting in the creation of secondary porosity. Many of the sandstones of Provinces A and B are of this type. The type and timing of carbonate emplacement (early pore-filling cement vs. late-stage replacement) in the sandstones is an important factor in determining the ultimate porosity of the rock. Carbonates that are emplaced early in the diagenetic history of the sandstones as pore-filling intergranular cements are most conducive to the eventual creation of an effective pore system. Dissolution of these cements usually results in the generation of significant interconnected secondary pores that yield high permeability as well as porosity (LOUCKS et al., 1977). This type of secondary porosity is uncommon in the sandstones of Provinces A and B due to the minor amounts of early pore-filling carbonate cements in the rocks.

Late-stage carbonates of replacement origin are also susceptible to dissolution, but the resulting secondary porosity is less likely to result in the creation of an effective pore system. The dissolution necessarily occurs late in the diagenetic history of the rock, and often results in the creation of vuggy porosity. Although significant porosity may be created, associated permeability is often quite low due to the lack of intercommunication among the pores. Most of the porosity in the sandstones of Provinces A and B is of this type.

At least a portion of the secondary pores in these sandstones may have formed on the outcrop as a result of surficial weathering. Because this type of secondary porosity may result in overly optimistic estimates of porosity in subsurface equivalents, it is important to differentiate it from subsurface dissolution porosity.

Conclusions

Diagenetic provinces can be recognized in the Verrucano Lombardo and Val Gardena Sandstones from the Lombardy, Dolomites, and Carnia regions of northern Italy based on the similarity of diagenetic history of the rocks. A specific paragenetic sequence exists for the sandstones of each province, but certain diagenetic features are common to all the sandstones. The early diagenetic history, including the infiltration of clay matrix, dissolution of labile framework grains, and formation of iron and manganese oxides, is similar for all the sandstones with minor differences in the relative importance of each feature. Mechanical compaction and, to a lesser extent, chemical compaction are the dominant agents of porosity destruction. The late diagenetic history is characterized by multiple episodes of carbonate replacement of detrital components, the exact details of which vary from province to province. Although minor amounts of early pore-filling nonferroan dolomite may be genetically related to the directly overlying evaporites of the Bellerophon Formation, the vast majority of carbonate in the sandstones is of a late-stage replacement origin and is probably genetically related to the Middle Triassic (Anisian) limestone and dolomite section.

Acknowledgements. — We would like to thank G.G. ZUFFA for numerous discussions on the regional geology and petrology of the Verrucano Lombardo and Val Gardena Sandstones. Petrographic thin sections were prepared by W.H. BATTEN and E.A. MILLER, and X-ray diffraction analyses were performed by W.I. FUGATE and B. STORJOHANN. R.A. WHITE provided invaluable technical assistance in the preparation and examination of samples with the scanning electron microscope. All the figures were drafted by C.E. CASADEI and the manuscript was typed by J. S. KLINE, L. F. BAIE, R.M. SLATT, E.V. ESLINGER, and E.R. NAIMAN reviewed the manuscript and offered many useful geologic, as well as editorial, suggestions.

Lavoro eseguito con i fondi M.P.I. 40% 1980/81 nell'ambito del IGCP Project n. 106 (Responsabile G.G. ZUFFA). Contributo finanziario M.P.I. 60% (Responsabile P. FAZZINI).

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