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THE GEOLOGY OF THE ROSAS-TERRESEO AREA (SULCIS, SOUTH SARDINIA)

BY

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ABSTRACT

Cambrian sandstones, limestones and slates, unconformably overlain by Ordovician and Silurian slates, intruded by Hercynian granodiorite and dolerite, and Alpine andesite, occur.

The traditional rock stratigraphic subdivisions of the sequences below the Ordovician unconformity are here proposed as formal units.

Iglesiente Group	Cabitza Formation	
	Metallifero Formation	Calcescisti Member Calcare Member Dolomia Member
	Arenarie Formation (base not seen)	

It is possible to distinguish Cambrian from Ordovician slates even where the basal conglomerate of the latter fails. As a consequence part of the official geological map (scale 1 : 100000, 1938) had to be revised.

The Cambrian and the Ordovician-Silurian rocks have undergone respectively four and three deformation phases with the development of slaty, fracture and crenulation cleavages. The large E-W folds of the Cambrian Sardic-phase are partly concentric (Arenarie and Metallifero rocks) and partly similar (slaty cleavage in the Cabitza slates). The second phase, also E-W, caused a further tightening of the "Sardic" structures and folded the Ordovician and Silurian rocks. The third deformation phase (N-S) was the Hercynian mainfolding, accompanied by fracture and crenulation cleavage. The fourth and last Hercynian phase (NW-SE and NE-SW) made a conjugate system of folds and cleavages. A specific structural pattern (domes, basins etc.) followed from the interference of these fold systems ("Schlingenbau"). Most folds are disharmonic as a result of differences in rock competencies of the Cambrian Formations. The Cambro-Ordovician unconformity has been partly obliterated by slip ("decollement") due to disharmonic folding above and below this plane.

Limestones have been partly converted into lime-silicate rocks by Hercynian hydrothermal and pneumatolytical action along irregular zones and an interesting skarn mineral paragenesis developed. The ore deposits (Pb, Zn, Cu etc.) are almost completely tied to the limestones of the Cambrian Metallifero Formation. The "lead-modelages" of galena samples from Min. Giuenni (N-Sulcis) and Min. Monte Poni (S-Iglesiente), both deposits in the Metallifero Formation, are about 600 million years old; samples from Min. Monte Vecchio (N-Iglesiente) and from an outcrop along the road Siliqua-Acquacadda, deposits respectively in a Hercynian quartzdike and a Cambro-Ordovician lime-silicate rock, are about 400 million years old. Almost all deposits have been rejuvenated during the Hercynian orogeny.

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1. Geological map, scale 1 : 25000
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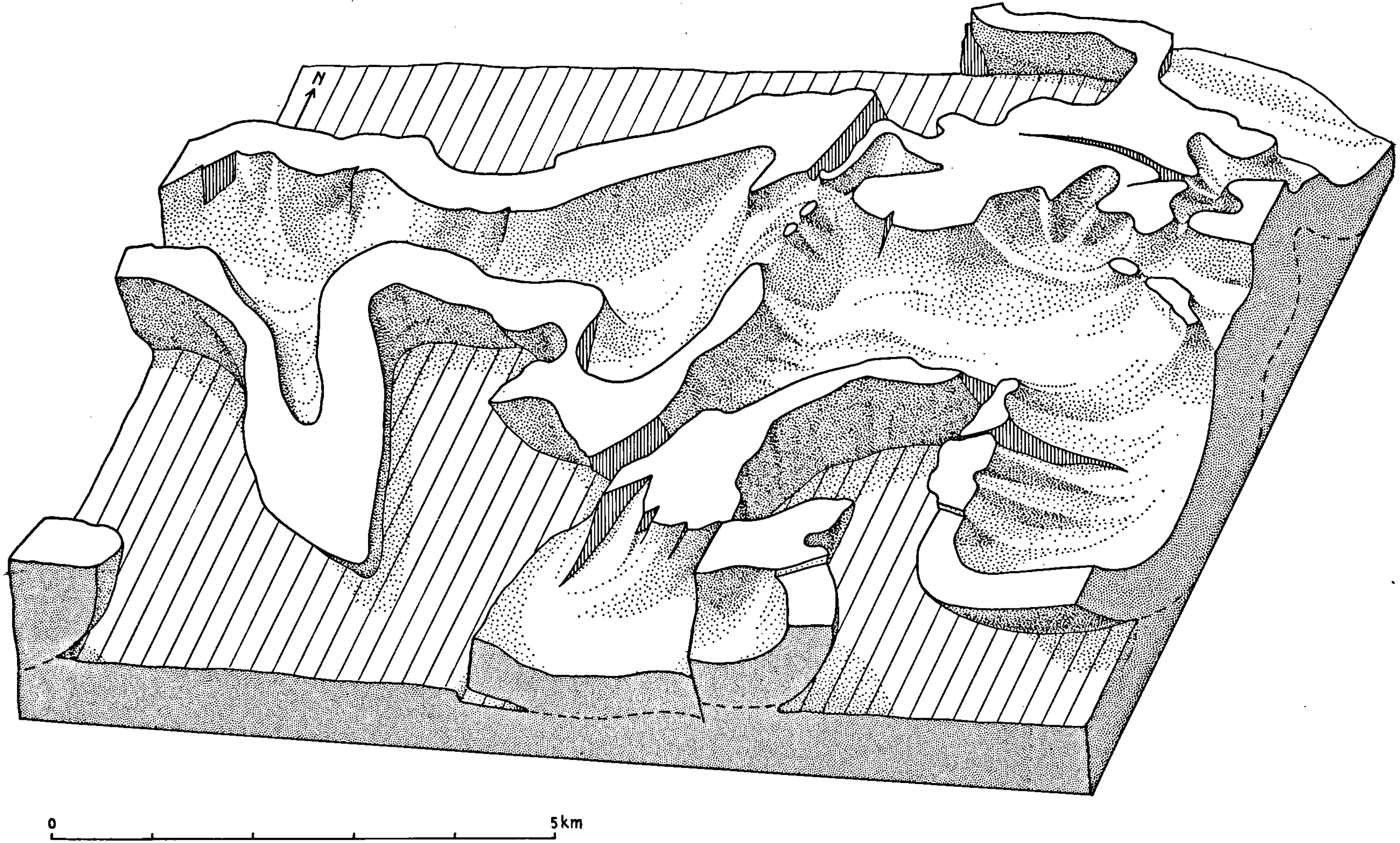

Fig. 1 Structure model of the Metallifero Formation showing the major folds and cross folds ("Schlingenfaltung") of northern Sulcis (see geological map, scale 1 : 25000).

INTRODUCTION

The mapping of a part of the Palaeozoic rocks of SW-Sardinia, has been carried out during the summers of 1961—1965 by students and graduates of the Department of Structural Geology of the Geological Institute of the Leiden University under direction of Dr H. J. Zwart and supervision of Prof. Dr L. U. de Sitter. The major aim of the investigations was the establishment of the succession of the various deformation phases.

The mapped area is intricately dissected into hills of low relief. The area is bordered in the north as well as in the south by distinct morphological units, respectively the Cixerri (rift) valley (a branch of the well known Campidano rift) and the basin of SW Sulcis. These units are both formed by the Alpine deformation. The hills reach an altitude of 723 m (M. Orri, co-ord. 42,7 — 78,9) and the elevation of the rift valley and the basin is respectively about 100 and 125 m; the amount of relief in the hills seldom exceeds 250 m.

The river pattern is mostly about N-S and in several cases obviously tied to fault zones and parallel to tectonic structures. Almost all rivers are dry during the summer.

Fig. 2 Terraces of Quaternary age along the border of the Tertiary Sulcis basin east of Terrubia. Photostation co-ord. 36,7 — 76,6, looking north.

The rocks of the area are sufficiently exposed, mostly in small outcrops between the more or less dense brushwood vegetation. The economic backbone of north Sulcis is mining and goat cheese production.

1 : 25000 scale topographic maps of the Istituto Geografico Militare (Florence) were used; i.e. the sheets Domusnovas (partly), Siliqua (partly), Acquacadda and Narcao of "Foglio 233 della Carta d'Italia". Mapping was carried out on a 1 : 25000 scale and partly on a 1 : 10000 and a 1 : 5000 scale.

Field work was carried out by Drs H. Brouwer and H. M. Kluyver in Iglesiente, and by D. Cosijn, M. Poelman and the present author in Sulcis. During our stay, field visits were made by Dr H. J. Zwart (4 ×), Dr G. L. Krol (2 ×) and Dr P. J. M. Ypma (1 ×); all of the Leiden University.

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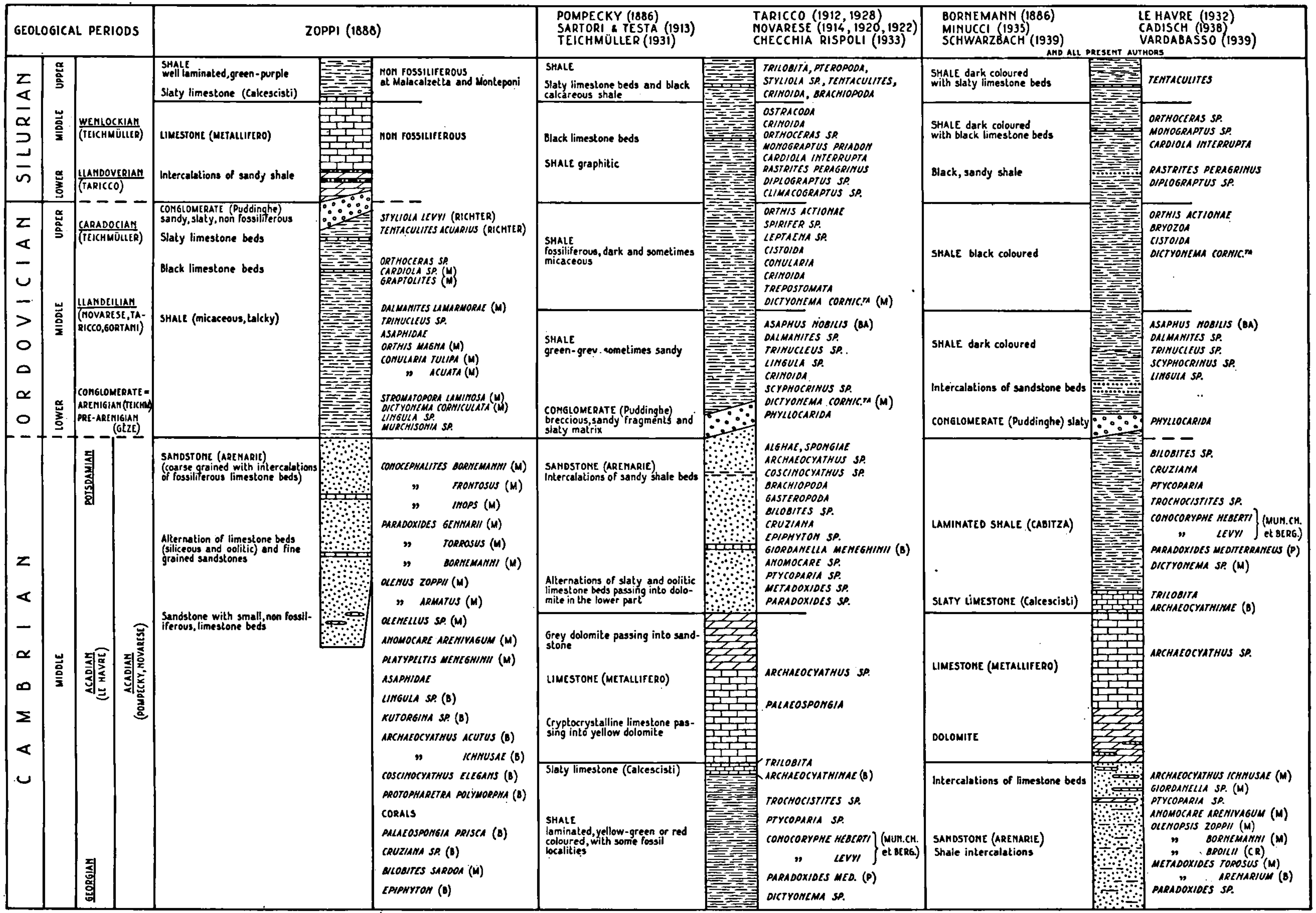


FOSSIL-DETERMINATIONS BY: (BA) = BARRANDE, G. 1880; (M) = MENEGHINI, G. 1886, 1888; (B) = BORNEMANN, J.G. 1886, 1891; (P) = POMPECKY, J.F. 1901; (CR) = CHECCHIA RISPOLI, G. 1938

Fig. 3 Stratigraphical sequence of the Palaeozoic deposits in Iglesiente and Sulcis according to various authors, composed by Zabelli (1948), translated and amplified by the present author.

STRATIGRAPHY

INTRODUCTION

Della Marmora (1857) was the first to describe the geology of Sardinia. His publications contain accurate descriptions of the rocks encountered on his voyages. The first fossils from Iglesiente, found by him near Fluminimaggiore, were determined by Barrande and Meneghini as Silurian. Bornemann (1886 and 1891) discovered several fossil localities and following his determinations he categorized the sandstones (Arenarie) as Cambrian. During the same years Meneghini (1888) published a number of trilobite determinations and Zoppi (1888) made the first stratigraphical division of the Lower Palaeozoic deposits of Iglesiente (fig. 3, first column).

Pompecky (1901) suggested some modifications on Zoppi's division. These suggestions were accepted by Novarese (1914), who introduced an entirely new and rather accurate division (fig. 3, second column). Novarese's stratigraphical division formed the base of the mapping of Iglesiente and Sulcis by the Italian Geological Survey.

Le Havre (1932-a) opposed the sequence of the Cambrian units proposed by Novarese and he suggested to reverse the stratigraphic column, because of the analogy between the Cambrian of the Montagne Noir in France and of Aragon in Spain and the Cambrian in Sardinia. Several authors agreed with this idea and Schwarzbach (1939) proved in different ways that the Arenarie forms indeed the oldest present Cambrian unit. Vardabasso (1940) recited a number of facts favourable for the new division and since then, in spite of severe objections raised by Novarese (1942), the stratigraphy as reproduced in the third column (fig. 3) was widely accepted. The exactness of this division for northern Sulcis shall be proved to be correct in this paper. Differences of opinion only exist on the dating of the different rock units. In spite of a number of fossil determinations, especially from Iglesiente, it is not possible to obtain the exact age of the different units. However, several tentative efforts have been made by different authors and their different opinions are represented in the column "geological periods" of fig. 3.

Until 1928 the geology of Sulcis was almost completely unknown, since all investigators concentrated themselves on the geological problems of Iglesiente. In that year Taricco pointed out that large parts of Sulcis are Cambrian and not Silurian, as was supposed by della Marmora. Soon it became obvious that the Cambrian rocks of Sulcis showed a completely similar development as those of Iglesiente. This similarity of the development of the Cambrian rocks over a large area (60 km) is remarkable and indicates uniform deposition conditions over the whole area.

The Cambrian rocks of S-Sardinia are divided into three definite rock stratigraphic units. The original names, as they are indicated on the geological map of the Italian Geological Survey (scale 1 : 100000, 1938), are rather long descriptive names:

"gruppo del scisti" (group of the slates)
"gruppo del calcare metallifero" (group of the metalliferous limestones)
"gruppo del arenarie" (group of the sandstones)

In more recent papers these names are abridged to "Arenarie", "Metallifero" and "Cabitza" (the village where the first fossils were found in these slates), without the addition Group, Formation or Member, but sometimes with the addition sandstone, limestone and slate.

According to the "Code of Stratigraphic Nomenclature" (A.A.P.G., 1961, 45, 5, p. 645—660) and especially the articles 6, 7, 9, 14 and 16, it is allowed to add "Formation" to the names mentioned above as they are so far never officially defined. There is a restriction, i.e. the fact that "Arenarie" and "Metallifero" are not geographic names. It would be unwise, however, to change names already well established. Hence the following devision is suggested:

<table>
<tr><td rowspan="3">Iglesiente Group</td><td>3 Cabitza Formation</td><td></td></tr>
<tr><td>2 Metallifero Formation</td><td>Calcescisti Member
Calcare Member
Dolomia Member</td></tr>
<tr><td>1 Arenarie Formation</td><td></td></tr>
</table>

Furthermore it is desirable to assemble the three Formations in one Group to describe all rocks beneath the Ordovician unconformity. Since Iglesiente is the original area where all stratigraphic study was carried out, the name Iglesiente Group is suggested to describe the three Cambrian Formations together.

It is so far impossible to divide the Ordovician and Silurian rocks of Sulcis into different units, since almost the whole sequence is composed of slates and only a few fossils are found. The Ordovician and Silurian rocks of Iglesiente are better developed and more fossiliferous and consequently a stratigraphic division, if possible, has to be drafted in Iglesiente.

The determinations of the fossils found in the different rock units by various authors, are listed in the columns of fig. 3 and will not be mentioned separately in the following rock descriptions.

CAMBRIAN (IGLESIENTE GROUP)

Arenarie Formation

The Arenarie Formation is the oldest rock unit of Sardinia and is exposed in Sulcis and Iglesiente. The rocks of this Formation are made up of a sandstone-slate alternation with intercalations of thin dolomite and limestone beds near the top. The base of the Formation is nowhere exposed; hence one only knows its minimal thickness, which is about 500 m in Sulcis and probably more in Iglesiente.

The sandstone is yellow-brown and the grain size varies from fine to coarse. Beside the normal components of quartz and mica, small fragments of feldspar crystals (plagioclase and K-feldspar) occur. Part of the cement of the rock is kaolin (alteration product of feldspar). This indicates that the Arenarie is formed by accumulation of material derived from erosion of a presumably crystalline Precambrian basement. This phenomenon was first observed by Bucca (1888). Sometimes white quartzites are found together with the sandstones. The slates are grey-green to brown and a bedding or a recognizable layering usually fails. Nearer the sandstone the sand content of the slate becomes higher.

In Sulcis sandstone is not so predominant in this Formation as it is in Iglesiente. Lateral facies changes are rather large in Sulcis, where it is obvious that the Arenarie rocks in subarea 1 and subarea 22 are far more sandy that the rocks in subarea 23 (fig. 20). The vertical alternation of sandstone and slate is very irregular and, apart from the limestone-dolomite intercalations near the top, no key beds can be found in this Formation in Sulcis.

The sandstone beds normally attain a thickness of 10 to 80 cm and crossbedding is rather frequent. Other sedimentary structures such as ripple marks, slumping, etc. are sometimes clearly seen in the sandstone-slate alternations. Especially in the rocks of the northern part of subarea 22 (fig. 20) one can make many top and bottom determinations based on the sedimentary structures. From these determinations it becomes perfectly clear that the Arenarie Formation is older than the Metallifero Formation. From the cleavage-bedding relation in this particular area we can draw the same conclusion. These two methods used together form perfect evidence, since we can decide from the cleavage-bedding relation (fig. 36) on which side of the structure a certain outcrop is situated and from the sedimentary structures we can settle top and bottom.

Near the top of the Formation intercalations of dolomite and limestone beds are found. The thickness of these beds normally varies between 20 and 100 cm, but exceptions occur. Laterally these intercalations wedge out rapidly. In the limestone and dolomite beds fossils are found at different places (see fossil localities on the map). In Sulcis these fossils are mainly archaeocyathids and especially the genera *Archaeocyathus* and *Coscinocyathus*; classification according to Bornemann (1886), who subscribed these fossils to the Coelenterata. Nowadays, however, they are incorporated with the Porifera by Shrock & Twenhofel (1953). The preservation of these fossils is bad as a result of recrystallization of the limestone and the dolomite. Consequently a species determination is impossible.

Some limestones are pisolitic. These pisolites are, just as the fossils mentioned above, only clearly seen on a weathered surface. The pisolites vary in size between 2 to 4 mm and are sometimes tectonically deformed. In Iglesiente many fossils were found during the last hundred years (fig. 3). Beside archaeocyathids the most important fossils of this Formation, found mostly in slate beds in Iglesiente, are trilobites (the genera: *Paradoxides*, *Metadoxides*, *Olenus*, *Olenellus* etc., see fig. 3).

Near the top of the Arenarie Formation the dolomite beds occur more frequently and become thicker. It is sometimes difficult to decide where the Arenarie Formation ends and the Metallifero Formation begins.

Metallifero Formation

The Metallifero Formation can be divided as follows:

3. Calcescisti Member
2. Calcare Member
1. Dolomia Member

The first two Members (dolomite and limestone) are mapped together and not distinguished separately on the map. This is done, while at least in Sulcis, it is extremely difficult to find the transition between the dolomite and the limestone. Sometimes the transition is formed by an alternation of the two rock types and sometimes these rocks merge laterally into each other. Above all, outcrops are scarce and dolomitization, most probably during the Hercynian, obscured the original composition at several places.

The name of this Formation ("Metallifero", which means metalliferous) is due to the important ore deposits, almost always bound to the rocks of this Formation. Fossils are seldom found as a result of recrystallization of dolomite and limestone by regional metamorphism and partial dolomitization of the limestone. The thickness of this Formation in Sulcis is about 400 m, but variations from 300 to 500 m occur.

1. *Dolomia Member.*— The transition from Arenarie rocks to Metallifero rocks is a gradual one. Normally the Arenarie Formation ends with a sandstone-slate-dolomite alternation and the lowest Member of the Metallifero starts with thick dolomite layers. Sometimes small sandstones beds, intercalated in the dolomite, are found and these are supposed to belong to this Member.

At the base of this Member well laminated, fine textured, grey-violet to dark dolomite ("dolomia rigata o listata") occurs. In these rocks many sedimentary structures on which top and bottom determinations can be done, are found (see also Vardabasso, 1950-a). This lamination is composed of an alternation of thin (some mm up to some cm), variously coloured, irregular layers. Near the top of this Member the dolomite become less laminated and more massive.

Two different types of dolomite occur in the Metallifero Formation. The dolomite of the lower part of the Formation (type A) was so far described as "primary" or "sedimentary" and the coarse and irregular dolomite bodies (type B) found throughout the Formation as "secondary". These terms are better avoided while "primary" suggests that the dolomite is formed by direct chemical or biochemical precipitation or by clastic accumulation of dolomite. This is most probably not true as most, if not all, dolomitic rocks in the world were originally laid down as limestones and have acquired their present composition as a result of early or late metasomatic alteration (Hatch, Rastall and Trevor Greensmith, 1965). The differences between the two dolomite types in Sulcis and Iglesiente can be explained in different ways:

a. The original composition and texture of the primary calcareous rock was diverse (e.g. lime-mud for type A and calcarenite for type B), and two different rock types developed during the dolomitization.
b. The dolomitization took place in two different stages. Type A was formed by early diagenetic or pene-contemporaneous dolomitization. Type B was originally consolidated as limestone and was later on (Hercynian?) subjected to dolomitization.

It seems very probable that the dolomitic rocks in Sulcis and Iglesiente were formed by the processes described in b.

The thickness of this Member is irregular and difficult to establish, but normally varies between 100 and 300 m with some exceptions. In some sections this rock (type A) completely fails; in other sections almost the whole Formation is composed of this rock.

In the dolomites (type A) badly preserved fossils, mostly archaeocyathids, are occasionally found and described from both Sulcis and Iglesiente. The transition to the Calcare Member is irregular.

2. *Calcare Member.* —Just as the texture of the dolomite (type A) of the first Member, the texture of the rock of this Member is cryptocrystalline. On a weathered surface the colour of this rock is light-grey. By fracturing it becomes obvious that this rock is almost a marble with a bluish-white colour, a waxy transparency ("calcare ceroide") and concoïdal fracture surfaces. At some places small intercalated sandstone beds are found.

Part of the limestone is recrystallized and part of it converted into dolomite.

The recrystallized limestone has a coarse texture and often a dark blue colour. The dolomite type B, a coarse textured, yellow-brown, mostly strongly weathered rock is found in irregular lenses. A recognizable layering normally fails in the rocks of this Member. This phenomenon is most probably due to recrystallization and dolomitization.

Sometimes a regular fracture system oblique to- and even perpendicular on the probable strike of the layering developed. This fracture system, often accompanied by "tectonic banding", is called by previous authors the "pseudostratification" of the Metallifero. Cadisch (1938) pointed already out that this "pseudostratification" is caused by the Hercynian deformations and in the opinion of the present author the Hercynian mainphase (N-S) is responsible for this phenomenon.

The absence of a recognizable layering gave many years ago rise to striking hypotheses about the origin of the Metallifero rocks:

a. The Metallifero Formation is an archaeocyathid reef (Zoppi, 1888).
b. The Metallifero Formation is a travertine deposit (Camerana, 1899).

However, these thoughts were never accepted. As a consequence of the absence of a layering at the surface, it is almost impossible to obtain an accurate stratigraphic section of these rocks.

Almost all large sulfidic ore deposits in Sulcis and Iglesiente are found in the rocks of this Member and generally located near the top. Fossils are very seldom found. Just as in the Dolomia Member the few fossils are archaeocyathids. The thickness of this Member, approximately the same as the Dolomia Member, varies from 100 to 300 m. The transition to the Calcescisti Member is usually abrupt. Lateral transitions of limestone (Calcare Member) to slaty limestone (Calcescisti Member) are rarely found.

3. *Calcescisti Member.* — The rock of this Member is a cream coloured marly limestone with a very strong and irregular fissility. Several theories were made to explain the origin of this special rock. According to Lambert (1896), this rock is either caused by dynamometamorphism of massive limestone or due to infiltration of carbonate-rich solutions into the shales of the Cabitza Formation.

Taricco (1930) extensively studied this special rock type and considering several facts he concluded that this rock originated by a sedimentation of small, lenticular, calcareous concretions together with pelitic material, and that the fissility of this rock is due to diagenetic action. These facts are:

a. the occurrence of many fossil fragments (trilobites, crinoids, archaeocyathids etc.),
b. the almost complete state of being tied to this specific horizon in the stratigraphy (exceptions occur in S-Sulcis, where this rock type is found intercalated in the top of the Arenarie Formation), and
c. the large and uniform lateral distribution of this rock in Sulcis and Iglesiente.

The present author agrees for the greater part with Taricco. Most probably the small concretions are diagenetic and not sedimentary. The appearance of this rock is completely different from the underlaying limestone and the overlaying slates. The fissility is always parallel to the strike of the line of outcrop and it is consequently not a tectonic cleavage.

Normally the composition is mainly calcareous, but a few outcrops of dolomitic "calcescisti" are found. The pelitic content of this rock, although subordinate to the calcareous, is such that this rock shows the same impermeability perpendicular to the layering as shales. The front of dolomitization and ore mineralization sometimes cease abruptly at the transition limestone (Calcare Member)-slaty limestone (Calcescisti Member); see also Taricco (1930).

The thickness of this Member varies between 20 and 50 m, but on some places this rock type fails. This is mainly caused by tectonic action, but it seems very probable too that this rock is not everywhere deposited. Due to lack of exposures it is difficult to study the transition of the slaty limestone to the slates of the Cabitza Formation, but it seems that the transition is rather abrupt.

Cabitza Formation

Cambrian trilobites were already found in 1896 in the slates near the railway station of the small village called Cabitza, a few kilometres south of Iglesias. Since then the name "Cabitza" is often used to describe the rocks of this Formation.

Fig. 4 Cross-bedded slates of the Cabitza Formation. Locality co-ord. 38,1 — 79,2. (2 ×)

The Cabitza Formation is almost completely composed of slates with intercalations of sandy slates and thin sandstone beds (up to 15 cm). Locally some rare and small limestone beds near the base are found. In thin sections it is seen that the slate is mainly composed of sericite and very minute quartzes. Beside these main constituents, chlorite and sometimes epidote occur. This last mineral indicates that the slate was slightly calcareous (Minucci, 1935). According to Novarese (1942) the Al-oxide content of the slates is 20%.

The lowest part of the Formation (several tens of metres) is composed of poorly layered slates. Cleavage is not well developed in that particular part. Hence, this is the likeliest place to look for fossils. These slates rapidly change into a thick sequence of very well laminated slates ("scisti listati"), heavily deformed by the different folding phases. The colour of the slates is mostly greyish-green, but sometimes purple. However, this last colour is also characteristic for the conglomerate and part of the slate of the Ordovician.

The most typical characteristic of the Cabitza slates in Sulcis and Iglesiente is the mainly tectonically, but also diagenetically (sedimentary structures frequently occur), distorted lamination. Of course, one has to be careful in considering this special appearance as determinative for the Cabitza, but it is correct for both Sulcis and Iglesiente.

A key horizon in the form of a thick sandstone bed or a sequence of different slates fails in this Formation in Sulcis and the rocks are heavily deformed by folding and cleavage. Consequently it is extremely difficult to establish the thickness. Furthermore the sequence is not complete since part of it is eroded before and during the deposition of the unconformable Ordovician conglomerate. The probable thickness of this Formation in Sulcis is at least 400 m.

No fossils are found in the top of this Formation. The few fossils found in the conglomerate and in the lowest part of the overlying slates are not very determinative for the exact age. It is possible that the conglomerate is Upper Cambrian, or that the top of the Cabitza is Lower Ordovician. For convenience sake, all Cabitza slates are supposed to be Cambrian in this paper and the conglomerate Ordovician.

ORDOVICIAN

Conglomerate

Unconformably on the slates of the Cambrian Cabitza Formation lies the basal conglomerate of presumably Lower Ordovician age. The "type locality" of this conglomerate is the coastal area of Nebida (Iglesiente), where this conglomerate is best developed and is found over 150 m thick. In this special area, enormous limestone blocks (over 50 m diameter) are bedded in the conglomerate, which is explained as a type of "wild-flysch" deposit.

The appearance of the conglomerate is very typical and characteristic as the rock is composed of slate fragments cemented in a shaly matrix with a striking purple colour (terra rossa colour) of both fragments and matrix. This rock is described under different names in the papers of these areas. These different names are "anagenite", "puddinghe" (= puddingstone), conglomerate, and breccia. As the pebbles are mostly flat and angular slate fragments and clearly preponderant over the matrix, the best descriptive name is sedimentary breccia. It is easier, however, to speak about slate-conglomerate in contrast to quartz-conglomerate, which one often encounters in Sulcis.

The unconformity is in principle an angular one. Since some slip due to disharmonic folding took place along the contact, an obvious erosion surface between the conglomerate and the Cabitza slates is only seldom found.

In Sulcis this basal conglomerate is poorly developed and fails in many places (see map). Only near Rosas the purple slate-conglomerate attains a thickness of about 100 m. The fragments of the slate-conglomerate are mostly derived from the Cabitza Formation. The size of the slate fragments varies from some mm (in the micro conglomerate) up to 15 cm. The composition of these fragments is more sandy than the average Cabitza slate. Pure slate fragments are easier destroyed by erosion than the more sandy ones. Consequently the last type is preponderant in the slate-conglomerate. Limestone fragments (up to some decimetres) are only occasionally found in the slate-conglomerate of Sulcis (e.g. locality with co-ord. 39,5 — 75,3). It is difficult to decide whether certain sandstone fragments in the conglomerate are derived from the Arenarie or from the Cabitza. It seems probable that occasionally part of the Arenarie is eroded too. Fragments of a crystalline basement, however, are never found. Hence it seems very probable that the erosion at the end of the Cabitza (Sardic phase) was only moderate.

Beside the slate-conglomerate small quartz-conglomerates are found. The pebbles of this conglomerate are well rounded, white quartz pebbles (fig. 5). The diameter of these pebbles is normally about 1 cm, but sometimes conglomerates composed of larger quartz pebbles (e.g. 5—10 cm in locality with co-ord. 39 — 72,3)

Fig. 5 Quartz conglomerate from the basal part of the Ordovician deposits. Locality co-ord. 39,1 — 74,2.

occur. These quartz pebbles are obviously derived from quartz veins of Cambrian age. The thickness and the lateral distribution of the quartz conglomerates are also irregular. Sometimes the base of the Ordovician deposits is formed by an alternation of small conglomerate beds (both types) and slates (fig. 6).

From the characteristic composition, irregularity in thickness and lateral distribution, and specific colour, some conclusions can be drawn. It is very likely that these conglomerates are channel deposits (probably partly fluviatile) immediately along a coast (short transportation). This coast was partly a cliff coast; otherwise the enormous limestone blocks in the Nebida conglomerates are unexplainable.

Slate

The Ordovician slates lie conformably on the conglomerate or, if conglomerate fails, unconformably on the Cabitza rocks. The transition conglomerate-slate is in many cases a gradual one with small conglomerate intercalations in the slates.

The lower part of the Ordovician slate sequence is mostly purple, just as the underlying conglomerate. According to Teichmüller (1931) these purple slates are formed by accumulation of "terra rossa". The likeliest explanation of the purple coloured deposits is, that they are formed by erosion of a deeply weathered and oxidized regolith (Pettijohn, 1956). As the transgression overflowed the last islands the deposition of this material ceased. This colour rapidly changes into a typical pale green, probably due to deoxidation. Alternations of slates of both colours occur frequently and indicate the sedimentary layering. Slates of these characteristic colours are almost always tied to the lower part of the Ordovician sequence, but they are not everywhere developed.

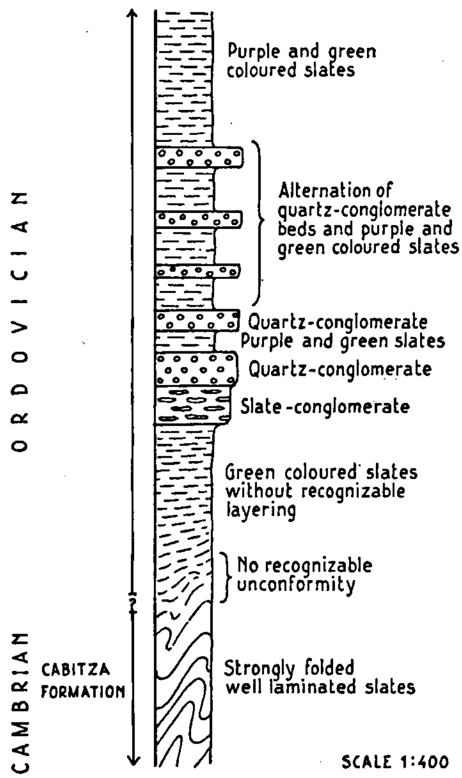


Fig. 6 Alternation of conglomerates and slates at the base of the Ordovician deposits. Locality co-ord. 40/41 — 72/73.

On the purple and green and poorly bedded slates follows an alternation of greenish-brown slates, sandy slates and sandstones with some rare limestone beds and small conglomerates. The sandy slates and sandstones are well exposed on M. Rosas (co-ord. 41,4 — 74,3). The small limestone and conglomerate beds, intercalated in slates, are found in the Rosas area (see geological maps).

In the top of the Ordovician slate sequence, fossils are found in different places (localities with co-ord. 46 — 75,8; 44,7 — 78 and 44,4 — 77,8). The fossils found by the present author in these localities are mostly badly preserved brachiopods.

In Iglesiente many fossils are found in the Ordovician rocks and especially in the upper part of the sequence.

On the whole the Ordovician rocks are poorly bedded in Sulcis and, consequently, it is extremely difficult to detect structures or to make stratigraphical sections and to measure or estimate with some accuracy the thickness of the sequence. The estimate of the thickness of the Ordovician rocks deposited in Sulcis is therefore a rough one and is between 250 and 400 m.

SILURIAN (AND POST-SILURIAN?)

The transition from Ordovician to Silurian rocks is a gradual one, hence the boundary line on the map is arbitrary. The Silurian is supposed to start where the colour of the slates changes into a darker tone.

The lowest part of the Silurian rock sequence is composed of poorly layered, fissile, dark slates with gasteropods (according to Taricco, 1926, *Tentaculites*). Some small limestone lenses are found in these slates, but higher up in the sequence the limestone intercalations become more frequent and the slates blackish.

On a weathered surface the colour of the slates is greyish, but on the fresh surface it is seen that the slates are black (graphitic). In these slates graptolites are found. The limestone beds are dark, coarse textured and fossiliferous (*Orthoceras*, crinoids and brachiopods). The thickness of these beds varies between 10—150 cm.

Higher up in the sequence (approximately after 60 m) the sand content of the slates increases rapidly and the colour changes into yellow-brown. North-east of the line with co-ord. 47—77 and 45—79 no graphitic slates and only a few limestone beds are found and a sequence of non-fossiliferous slates and sandstones is exposed. According to Taricco (1926) and the authors of the geological map of the Italian Geological Survey, these latter rocks are post-Silurian, which is probable, but cannot be proved in this particular area. The rocks here are poorly exposed, but it seems that the sequence of graphitic slates and limestones to sandy slates and sandstones is conformable. Consequently the whole sequence is indicated in one colour on the present map (scale 1 : 25000).

The thickness of the whole sequence here exposed is about 100 m.

TERTIARY AND QUATERNARY

The Palaeozoic mountain core is bordered by large structural and morphological units as the Cixerri (rift) valley in the north and the large basin of southern Sulcis (also subsided along faults). According to Teichmüller (1931) these large Alpine structures originated at the end of the Cretaceous. Since then these "basins" are filled up with sediments and this process is still going on.

Along the borders of the mapped area rocks of Tertiary and Quaternary age are lying unconformably on Lower Palaeozoic rocks. On the geological map (scale 1 : 100000) of this area these rocks are divided into the following sequence:

Quaternary {
4. alluvium
3. scree
2. travertine
1. fluvial deposits (sand and conglomerate)

Tertiary	2. marle, sandstone and conglomerate, non fossiliferous (Oligocene-Miocene?) 1. sandstone, limestone, marle, shale and conglomerate (Eocene?)

On the map of the present author (scale 1 : 25000) the rocks of the Tertiary and the fluvial deposits of the Quaternary are mapped together. The study of these deposits was not the aim of the present author. Chinaglia (1925) described the Tertiary deposits between Narcao and Acquacadda in some detail.

CONCLUDING REMARKS

The Cambrian rock sequence (sandstone-limestone-slate) indicates a deepening of the sedimentary environment due to subsidence of the basin accompanied by a growing transgression. The sandstones and slates of the Arenarie Formation are probably littoral to shallow neritic. The following limestone and slate Formations (Metallifero and Cabitza) are more neritic deposits.

During the sedimentation of the Arenarie Formation the basin subsided gradually in such a manner that the conditions remained littoral. At the transition to the Metallifero these conditions changed slowly into neritic by increasing subsidence of the basin. At the end of the Cambrian, after the deposition of the Cabitza slates, the rocks were folded and uplifted by the Sardic phase.

Erosion started as soon as the first anticlinal ridges were uplifted above sea level. An irregular and characteristic purple coloured basal conglomerate developed in the "valleys". This conglomerate is mainly composed of slate fragments with locally an accumulation of limestone fragments. This composition indicates very short transportation.

In Sulcis the conglomerate fails at many places and the thickness varies rapidly. On the Metallifero rocks this conglomerate is nowhere developed on the unconformity and the Ordovician sequence starts directly with slates. The conglomerate represents channel deposits partly along an ancient cliff coast. The terra rossa sedimentation lasted until the transgression overflowed the last elevations.

After the transgression a neretic environment with preponderant clay sedimentation developed. At the end of the Ordovician and during the Silurian the environment changed and resulted into the development of graphitic shale which is characteristic of the Silurian deposits all over Europe.

It is very difficult in Sulcis to obtain information about the original direction of the material supply during the Cambrian and the Ordovician. In some papers a southern foreland is suggested but the present author was unable to find such indications in Sulcis.

TECTONICS

INTRODUCTION

Previous authors

During the last century many geologists were engaged with the problems of the complicated structures in Iglesiente and Sulcis. The geological survey was carried out mainly by mining engineers and geologists of the Italian Geological Survey. Regularly foreign geologists, attracted by the numerous problems not only on tectonics, came to Sardinia.

In his extensive work on Sardinia della Marmora (1857) already described the E-W and the N-S directions of the structures in Iglesiente and Sulcis. After him all authors mentioned these two obvious structural directions, but nobody came further than the assumption, that the E-W was a Caledonian and the N-S a Hercynian direction.

Lambert (1896) pointed already out that it is extremely important to distinguish cleavage from bedding in the slates. In those areas, where a good recognizable bedding is present beside the cleavage, the distinction is not difficult, but several investigators were mislead by the poorly bedded Ordovician slates.

South-west of Iglesias Testa (1914) found continental deposits of Upper Carboniferous-Lower Permian age obviously undisturbed by folding. The Hercynian deformations are consequently older; presumably of Carboniferous age.

In his important work on the geology of Iglesiente Novarese (1914) made some important remarks about the deformation of the pebbles of the Ordovician conglomerate by the N-S cleavage folding. Novarese and Taricco (1922) were the first who considered this conglomerate as a post-tectonic basal conglomerate. They supposed an important folding phase at the end of the Cambrian. Most likely important vertical movements did not occur during the Sardic phase, while the basal conglomerate contains no fragments of a crystalline basement. The Sardic phase was not accompanied by important magmatic action.

According to Teichmüller (1931) the Sardic phase caused isoclinal folds, mostly slightly overturned to the south, accompanied by fracture cleavage. These overturned folds were caused by movement from north to south. As far as the cleavage is concerned, Teichmüller was probably mislead by cleavage of later phases. According to the same author the main folding of the Hercynian orogeny is post-Lower Carboniferous. The vertical uplift and the following erosion during the Hercynian is considerable, while Lower Permian deposits are lying unconformably on Cambrian rocks. In analogy with Corsica Teichmüller supposes that the large and important granite intrusions belong to the Sudetic phase of the Hercynian orogeny.

Part of the area investigated by the present author was already mapped and described by Catalisano (1930). The structural pattern of the area could be explained simply: E-W structures, N-S refolded.

Cadisch (1938) mentioned large and regularly developed E-W folds of Cambrian age, on which the Ordovician rocks lie unconformably. He described the interference pattern caused by the perpendicular fold systems with the term "Schlingenbau".

In a number of articles Vardabasso (1950 b, 1956 and 1960) described the tectonics of this part of Sardinia. In one of his papers (1956) he mentioned the disharmony of the Sardic folds and ascribed this to the lithologic differences between the Cambrian Formations. In the same article he mentioned the "Schlingenfaltung" in Sulcis between Narcao and Villamassargia and points out the "Palaeozoic direction" of the Cixerri valley (branch of the Campidano rift).

Gèze (1952) posed three different hypotheses to explain the tectonics of the Iglesiente area. These hypotheses were drafted to explain overturned structures in Iglesiente as seen for example at Mte Acqua (north of Domusnovas).

In the extreme south of Sulcis (Teulada area) the Cambrian rocks are less deformed than in northern Sulcis and Iglesiente (Salvadori, 1961). Salvadori wrote that the Sardic phase in that area formed large folds with N-S to NW-SE axes and that later on the Hercynian orogeny accentuated these Sardic structures. It seems to the presenta uthor, however, that only one folding occurs in southern Sulcis with roughly a N-S direction and axial plane fracture cleavage. These folds have the same direction and appearance as folds of the Hercynian main phase and it seems that the first two folding phases do not occur in that area.

Schwarzbach (1952) surely underestimated the tectonical problems by saying that "Gegenüber dem komplizierten Bau der deutschen Kaledoniden und Variscíden ist die Tektonik des sardinischen Kambriums aber einfach".

Graulich (1953) maintained that:

a. the N-S cleavage folding belongs to the Caledonian orogeny,
b. this folding is the oldest present deformation phase, and
c. the conglomerates are not basal conglomerates of the Ordovician, but intercalations in the Cambrian slates.

The present author, however, does not agree with these conclusions, as will be shown in this chapter.

Arthaud (1963) published a paper on the tectonics of the area north of Domusnovas (Iglesiente). He found the same four folding phases as we already established in Sulcis and part of Iglesiente. His publication was the first after a good many years that brought new light in the structural problems. The second folding in that part of Iglesiente seems to be stronger than the Sardic phase and a regular fracture cleavage developed. The third phase (N-S) cleavage is not vertical in that area and part of the structures are overturned. Only one set of the conjugate system of the fourth phase is found in that area.

In addition to Arthaud's paper Poll and Zwart (1964) published a short paper on the tectonics of northern Sulcis. In this paper the slaty cleavage belonging to the Sardic phase and the conjugate system of the fourth deformation phase were mentioned for the first time.

General remarks

For a better understanding of this chapter it seems useful to discuss briefly several notions. In this chapter the following classification of cleavage is used (Knill, 1960):

slaty cleavage
fracture cleavage
crenulation cleavage.

Slaty cleavage is easily recognized, especially in thin sections, by the characteristic parallel fabric of the minerals (e.g. sericite). The distance between the cleavage planes is limited by the thin laminae formed by the basal cleavage of micas and consequently infinetely small. The typical shining surface, due to orientation of the mica flakes, is very useful for recognizing in the field.

Fracture cleavage slivers the rock into narrow zones called microlithons (de Sitrer, 1964). The distance between the cleavage planes is larger than by slaty cleavage. Most of the mica flakes are found concentrated and orientated on the cleavage planes.

Crenulation cleavage refers in general to secondary cleavage, that micro-folded a pre-existing slaty cleavage. About this cleavage type Knill (1960) wrote: "strain-slip cleavage is not a form of fracture cleavage developed essentially by brittle rupture, but must be regarded, in its own right, as a distinct cleavage phenomenon" and further on "a term such as 'crenulation cleavage' is preferable to 'strain-slip cleavage' ".

The triaxial system of Sander (1948) is specifically avoided, because of the difficulties of reconciling the geometric form with the dynamic interpretation. Further it is practically impossible to use this system once refolding has taken place. The use of the strain ellipsoid with its three axes A, B and C, respectively the longest,

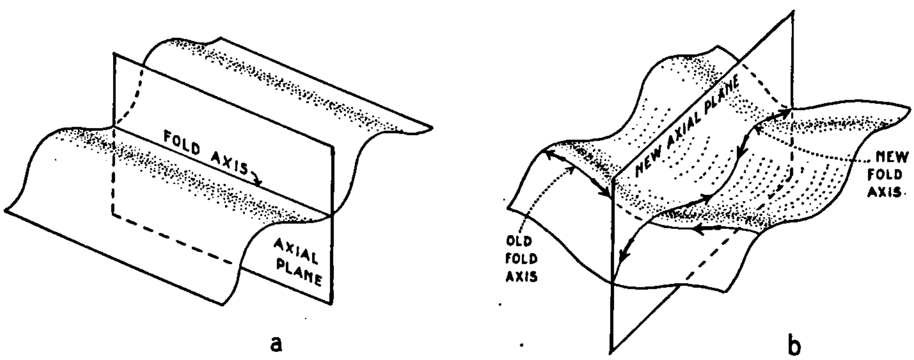


Fig. 7a First folding, resulting in folds with vertical axial planes and horizontal fold axes.
Fig. 7b Crossfolding resulting in folds with vertical axial planes and fold axes with different orientations.

median and shortest, also tends to lead to confusion due to the similarity with the tectonic system of Sander. Hence in this paper the terms elongation axis, fold axis, δ-lineation and stress direction, etc., are used.

When successive deformation phases occur one can establish the right succession in those outcrops where these deformations are found together. If an axial plane or cleavage of a fold is deformed by another folding phase, the succession is proved. The cleavage plane is one of the most important planes of reference, but one has always to be careful as exceptions occur.

The presence of successive folding can also be deduced from stereograms. Folding of a bedding plane about one axis produces a girdle of poles to that plane in the diagram. The fold axis is normal to the girdle. When an axial plane cleavage is developed, the poles to the cleavage plane produce a point maximum, sometimes partly spread around the fold axis, due to fanning of the cleavage in the folds. The lineations, which result from intersection of cleavage and bedding, produce a point maximum, which coincides with the fold axis. Folding of such structures about an oblique axis will produce a spread of the original bedding plane girdle and the point maximum of the fold axes and the δ-lineations of the first folding are spread into a girdle. Perpendicular to the plane through this girdle we find the new fold axis. The fold axes and δ-lineations of the refolding are also spread into a girdle; the poles of the new cleavage planes, however, produce a new point maximum (fig. 7). The spread of lineations and axes accordingly is due either to superimposition on a curved surface, or to folding of original parallel lineations and axes. The poles to the bedding planes and to the various cleavage planes, fold axes and intersection lines have been plotted on Schmidt's equal area stereographic nets. The diagrams are lower hemisphere projections. The number of points bears no relation to the intensity of the feature encountered.

In this paper the author uses the term "axial plane trace", in the sense of the intersection of the axial plane with the terrain surface (Fleuty, 1964).

The term "minor structure" will be used in the sense of small structures larger than the size of microscopic observation, but too small to be visible on a geological map or on aerial photographs.

Parasitic folds (de Sitter, 1958) are small folds of competent layers within larger folds.

The symbols used in this paper are:

ss	– bedding plane
s_1, s_2, s_3, s_{4a} and s_{4b}	– successive cleavage planes. The numbers of these planes correspond with the numbers of the deformation phases to which they belong.
π-ss	– pole of bedding plane
π-s ($_{1}$, $_{2}$, $_{3}$, $_{4a}$ or $_{4b}$)	– pole of cleavage plane of successive deformation phases
δ- ($_{1}$, $_{2}$, $_{3}$, $_{4a}$ or $_{4b}$)	– intersection of ss with respectively s_1, s_2, s_3, s_{4a} and s_{4b}

For a better understanding of the discussion of the folding phases their sequence and main characteristics are listed in the following scheme.

Deformation phase	Fold axis	Axial plane and cleavage
1. Sardic (early Caledonian)	E-W	vertical E-W s_1
2. } Hercynian (?)	E-W	vertical E-W s_2 (subordinate)
3. } Hercynian (?)	N-S (NNW-SSE to NE-SW)	vertical N-S (NNW-SSE to NE-SW) s_3
4. } Hercynian (?)	vertical to NW-SE and NE-SW	vertical NW-SE s_{4a} NE-SW s_{4b} cleavage locally developed

FIRST FOLDING PHASE (SARDIC PHASE)

The Sardic folding occurred at the end of the Cambrian or at the beginning of the Ordovician and gave rise to folds with vertical E-W axial planes. The sequence, between the beds with the youngest Cambrian fossils found at the base of the Cabitza Formation and those with the oldest Ordovician fossils, represents a considerable interval of time during which the Sardic phase took place.

Stille (1939) called this phase the Sardic folding phase and he pointed out that this early-Palaeozoic folding phase, however feeble, is known from places over the whole world. This folding phase was connected by Stille with the Caledonian orogeny, although this orogeny is not known from this part of Europe. Several authors prefer to speak about a pre-Silurian orogeny. This is not a good name either, while the real Sardic phase is only known from a small area: Iglesiente and Sulcis.

Fig. 8 Detail of the unconformity of Ordovician conglomerate upon Cabitza slates near Villamassargia. Ca = Cabitza, Co = conglomerate. Locality co-ord. 47,7 — 68,4.

As far as the present author knows from literature, no dated Cambrian rocks are found in other parts of Sardinia. Hence, nothing can be said about the extension of the Sardic fold system to the north, and the east. To the south, however, structures of this phase are missing in the Cambrian rocks of the Teulada area. Therefore it seems, that the term "orogeny" is far too comprehensive to describe this rather local deformation phase.

The "type locality" of the Sardic phase is the coastal area around the village of Nebida in Iglesiente about 15 km WNW of the mapped area. It seems, however, that part of the contacts of Ordovician conglomerates with Cambrian rocks are tectonic contacts in that area (Teichmüller, 1931). In several cases the unconformity is clearly an angular one, e.g. M. Uanni, west of Fluminimaggiore, and it is obvious that the Cambrian rocks were folded before the erosion followed by the deposition of the conglomerate took place (Kluyver, 1965).

Besides in the Iglesiente area (Nebida, Gonnesa, Fluminimaggiore and north of Domusnovas), this basal conglomerate is also developed in Sulcis, although not in a large extension and not everywhere on the Cambro-Ordovician contact. The unconformity in Sulcis is in many cases not obvious in the field, but evident on the map.

One of the best examples of the unconformity in northern Sulcis can be observed in the field immediately west of Villamassargia (co-ord. 47,6 — 68,3). The angular contact of Ordovician conglomerate on the Cabitza is evident and amounts to 60° (figs. 8 and 9). The contact is rather sharp, but in more detail an irregular erosion surface can be observed between the two rock types. Another place where the unconformity occurs, is found along the road from Siliqua to Acquacadda (co-ord. 41,6 — 82,5). No direct contact can be studied here, but as one compares the moderately folded Cabitza slate along the road with the barely folded Ordovician sandstone and

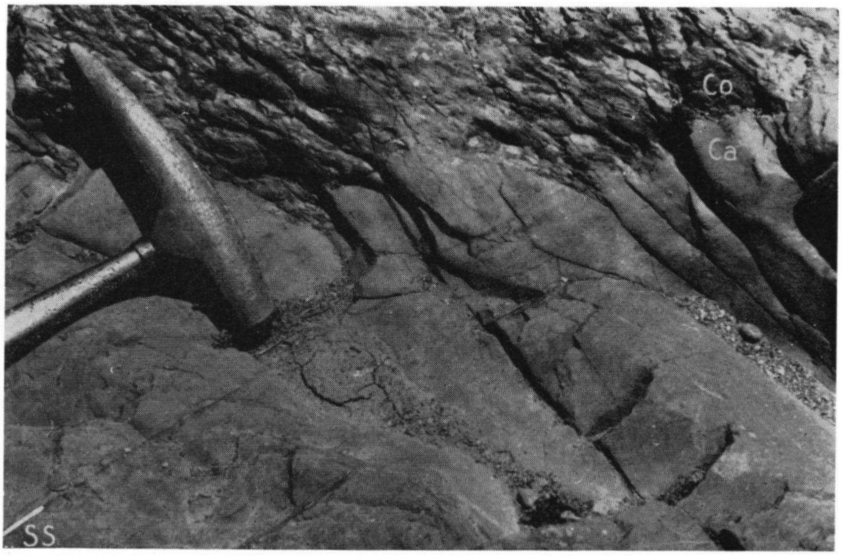


Fig. 9 Angular unconformity of Ordovician conglomerate upon an irregular erosion surface, cut in slates of the Cambrian Cabitza Formation. The angle of discordance is about 60°. Locality co-ord. 47,7 — 68,4.

slate immediately above the road, it is clear that the latter are lying unconformably on the former. The best evidence of the unconformity is found on the geological map and the profiles of this area, where it is clear that the contact cuts across the whole Cabitza Formation.

Recently, there has been a tendency to consider the contact of Ordovician upon Cambrian rocks as a thrust or nappe contact. On several places a fault can indeed be detected along the contact of Ordovician slates with Metallifero limestones (large quartz-breccias, see map). This, however, is caused by later folding of these rocks of different competencies (see N-S profiles 71, 72 and 73). There is no need to assume large thrust movements along the base of the Ordovician rocks on the Cambrian rocks in Sulcis.

The reason for the obscurity of the unconformity in the field lies in the following facts:

a. The direct contact between the Cambrian and Ordovician rocks is seldom exposed.
b. Before the deposition of the conglomerate, a weathering soil developed sometimes in the Cabitza shales with the result, that the transition zone in that case is rather broad.
c. The conglomerates in Sulcis are only poorly developed and are absent in many places along the contact.

Some geologists were mislead to such a degree by the apparent conformity and the fact that faulting occurred along the contact, that they came to the opposite conclusion that this conglomerate is not a normal sedimentary basal conglomerate,

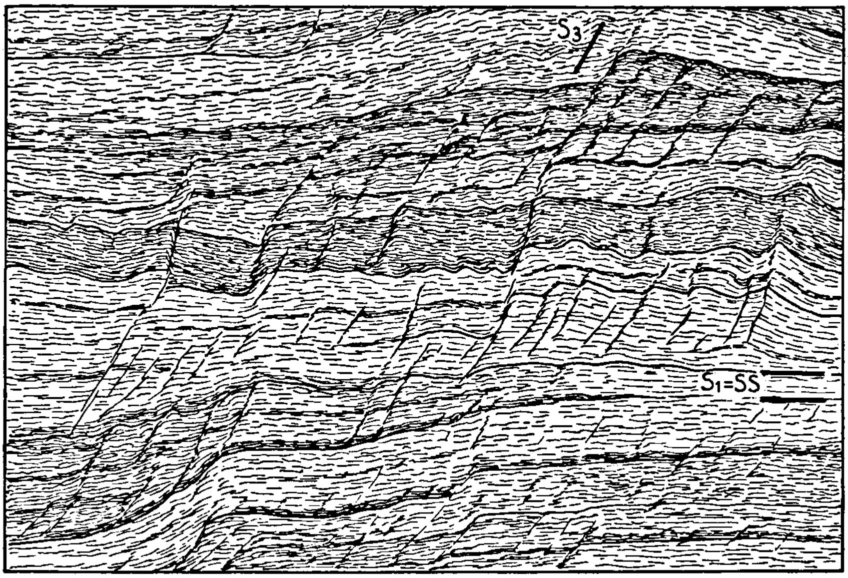


Fig. 10 Cabitza slate with s_1 parallel to ss (thin section). Locality co-ord. 39,5 — 76. (20 ×)

but a concordantly sedimentated sequence that acquired his breccious appearance by later tectonization while the material was not yet lithified. They maintain therefore that the Sardic phase is postconglomerate (del Bono, 1965 et al.).

One recognizes the unconformity well, if one knows more about the tectonics of the region. The Cambrian rocks have been folded one more time and normally have one more cleavage than the rocks of Ordovician and Silurian age and therefore a certain difference in deformation intensity is observable.

The folds ascribed to the Sardic phase vary in size from very large to very small. The massive Arenarie and Metallifero Formations were folded into large concentric folds with an average wave-length of approximately 8 km and an average amplitude of about 3 km (see map and profiles). The slates of the Cabitza Formation on the other hand were subjected to similar folding (fig. 16a). The large E-W folds, seen on the geological map of the Rosas-Terreseo area and which can also be seen on the maps of Iglesiente, belong mainly to this phase. The first Hercynian deformation has folded also around E-W axes, but there is a remarkable difference between the E-W folded Cambrian and the E-W folded Ordovician. If one subtracts the effect of the first Hercynian folding from the large E-W structures there still remain distinct E-W structures. The main feature of these large folds is the disharmonic character, due to strong differences in lithology, with the thick limestone and dolomite Formation (Metallifero) underlain by the sandstone Formation (Arenarie) on the one side and overlain by the slates of the Cabitza Formation on the other side. The massive and thick Arenarie and Metallifero Formations determined the size of the major folds to which the Cabitza slates had to adapt themselves (see profiles).

During this phase a slaty cleavage (s_1) sometimes developed in the Cabitza slates, which often parallels the bedding (fig. 10). From this parallellism one can assume, that:

a. the folding in the Cabitza slates is partly isoclinal with s_1 as axial plane cleavage, or
b. the folding in the Cabitza slates is concentric with a concentric cleavage development subparallel to the bedding (de Sitter, 1964).

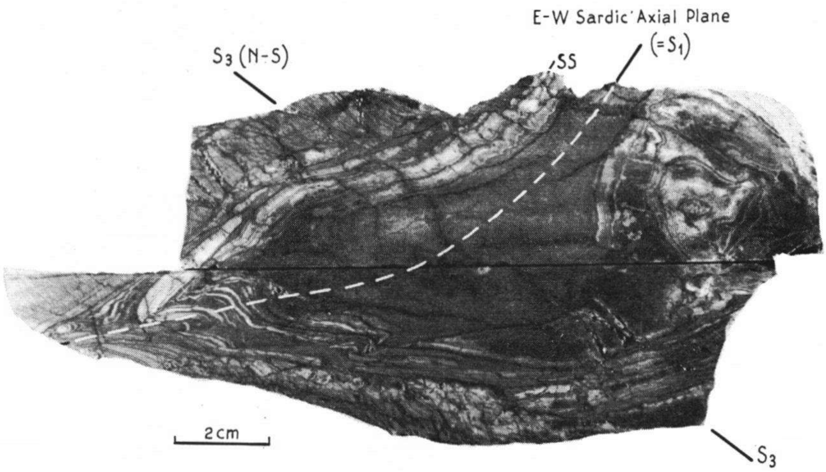


Fig. 11 Sardic minor fold in Cabitza slate, refolded by the third phase (s_3). Locality co-ord. 41,7 — 70,5.

Fold hinges are difficult to find, but examples, demonstrating that this is axial plane cleavage, have been found (figs. 11 and 12).

With the aid of microscopic study of thin sections of oriented slate samples, it is not difficult anymore to find fold hinges or parts of folds (figs, 13, 14 and 15). From these examples it seems that the Sardic cleavage is an axial plane cleavage and not a concentric one. The Sardic cleavage is developed as a perfect orientation of new formed sericite crystals, sometimes forming a strong lamination, which resembles the original bedding (fig. 15). In almost all thin sections, the relation of this slaty cleavage with the almost always present crenulation cleavage of the third phase (N-S) can be observed and it is clear that the crenulation cleavage deforms the slaty cleavage and consequently belongs to a later deformation.

It seems very probable, that the Cabitza slates west of Terreseo are folded in one large isoclinal fold with a vertical axial plane. All δ_3-lines dip steep to vertical and no hinges of Sardic minor and major folds are found in that area.

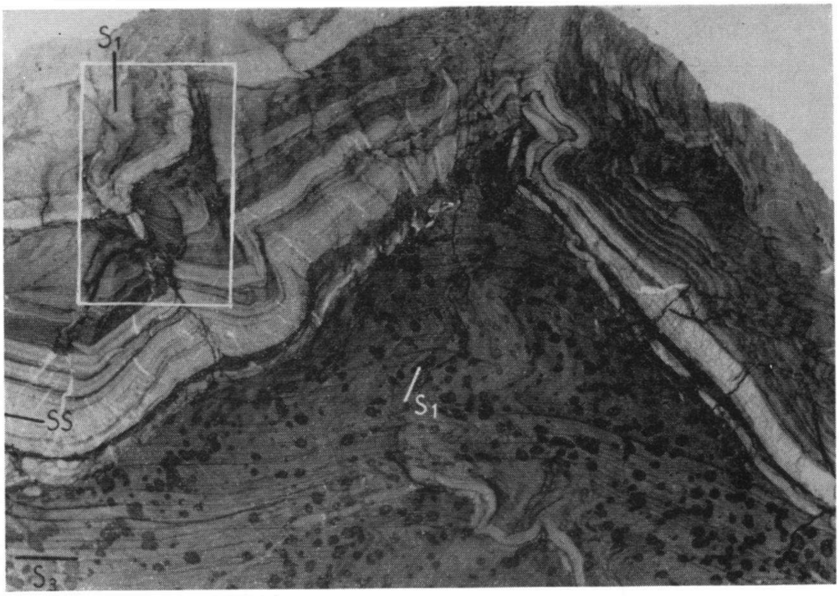


Fig. 12a Sardic minor fold in spotted Cabitza slate with axial plane slaty cleavage (s_1) and tectonic banding parallel to s_1, refolded by the third phase (s_3). Locality co-ord. 36,7 — 78,9. (1,5 ×)

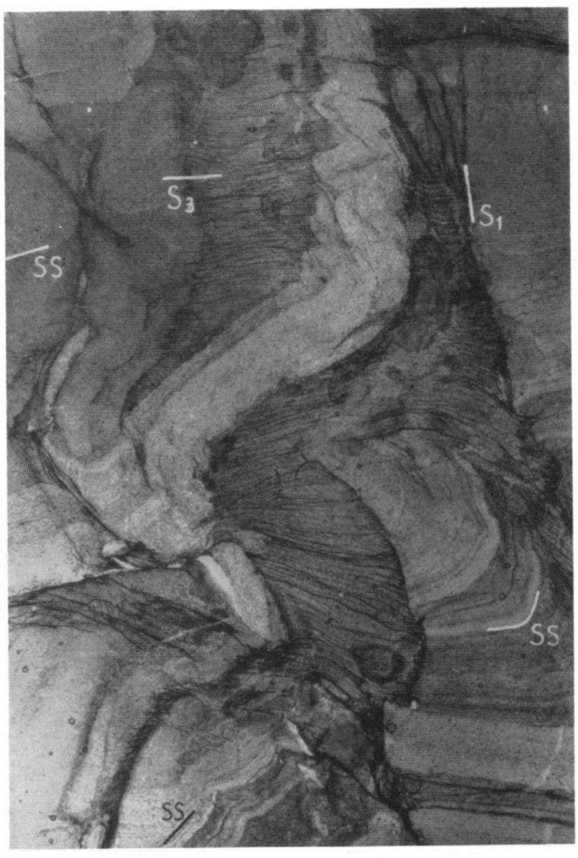


Fig. 12b Detail of fig. a showing tectonic banding parallel to the Sardic slaty cleavage (s_1). (8 ×)

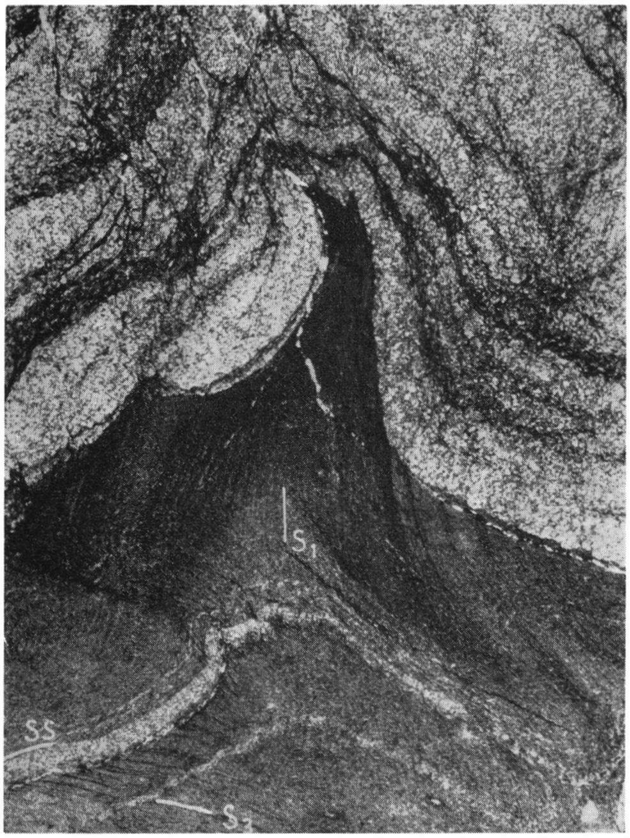


Fig. 13 Sardic micro fold in thin section of Cabitza slate with axial plane cleavage (s_1), slightly refolded by the third phase (s_3). Locality co-ord. 41,2 — 63,8. (10 ×)

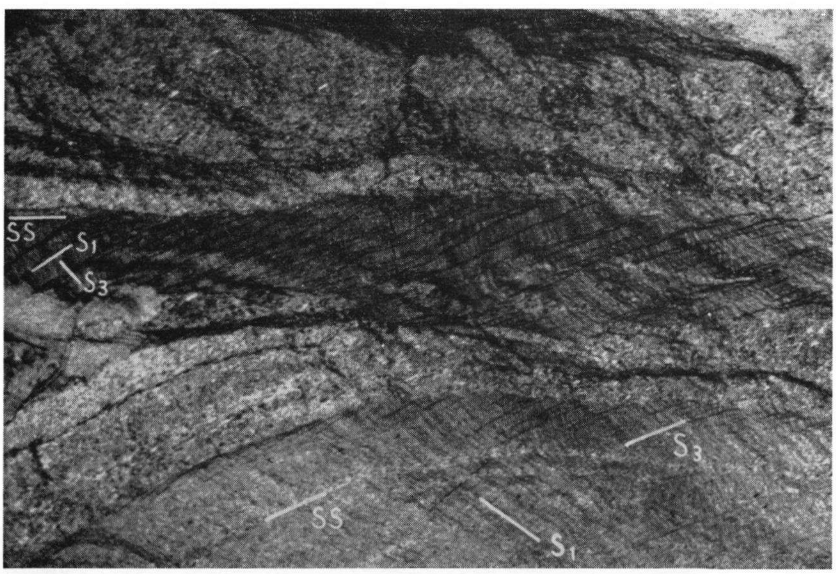


Fig. 14 Part of Sardic micro fold in thin section of Cabitza slate. Locality co-ord. 41,7 — 64,2. (12 ×)

The Cabitza slates some kilometres east of Terreseo are not so strongly folded by the Sardic phase. When we look at the δ_3-diagram (fig. 23, no 13) of subarea 13 (fig. 20), we see that the δ_3-axes are almost horizontal in this area. This proves that at the beginning of the third deformation phase the bedding planes were only gently folded or not folded at all, or that the bedding planes were folded in isoclinal folds with horizontal axial planes, but this last possibility is out of the question. East of this subarea, in the Rosas region, indications of a more intensive Sardic folding occur. Another convincing indication of a less intensive Sardic deformation is the lack of a Sardic cleavage in the Cabitza slates of this area. It is also striking, that the central part of the Rosas-Terreseo area (see map) bears the most obvious marks of the N-S deformation. A slightly folded area refolds apparently easier than a strongly folded one.

A schematic N-S section through the large E-W Rosas-Terreseo syncline after the Sardic phase, but before the Hercynian deformations, is given in fig. 16a. The Sardic trend in the Cabitza ENE of Terreseo is wiped out by the third (N-S) deformation.

Especially in the more quartzitic Cabitza rocks the s_1 is missing. In these rocks slaty cleavages could not develop as there was not sufficient mica to re-orient and for some reason a fracture cleavage did not develop. The cleavage of the Sardic phase originated almost always as a slaty cleavage. A Sardic fracture cleavage is sporadically found in thin sections. In those cases, where slaty cleavage parallels the bedding and small competent beds occur, we find an indistinct fracture cleavage in these competent beds, cutting the bedding under a very acute angle. As the younger cleavages (s_2, s_3 and s_4) mainly originated as fracture cleavages, it is conceivable, that it would be very difficult to distinguish a Sardic fracture cleavage.

Although one needs a microscope to decide whether a thin section of a certain Cabitza slate sample contains a Sardic slaty cleavage or not, one can acquire indications in the field whether such a cleavage occurs or not. As the slaty cleavage often parallels the bedding, no lineations are made. Slaty cleavage consists of a mineral orientation (mica, chlorite, etc.). These micas are not the sedimentary muscovites which one often sees on the bedding planes, but consist of a large quantity very small sericite crystal plates, which render the plane on which they are concentrated a lustrous sheen.

Poll and Zwart (1964) were the first who described the Sardic slaty cleavage. The reason, that this cleavage is found only a short time ago, is due to the fact, that this cleavage is only well seen in thin sections and structural analysis with the help of thin sections to amplify field data is not yet a commonly used method in Sardinia.

Another proof of the existence of a Sardic cleavage is sometimes found in the pebbles of the Ordovician basal conglomerate. This conglomerate consists mainly of fragments derived from erosion of the Cabitza formation. These fragments can sometimes be seen retaining the Sardic cleavage. In most cases, however, the Cabitza pebbles have a rather high quartz content and we have seen before, that in the more sandy Cabitza rocks no cleavage would develop. On the other hand the more pelitic fragments, which contained the s_1, normally were destroyed by weathering before deposition could take place.

When cleavage and bedding are parallel another problem presents itself, i.e. the occurrence of tectonic banding. It is a commonly known fact, that a tectonic banding can originate parallel to the cleavage. Such a tectonic banding can develop so strongly, that the original bedding is erased. If a certain cleavage parallels a certain banding, we have to ask ourselves whether this cleavage is parallel to the bedding, or whether this cleavage parallels its own tectonic banding. In the last

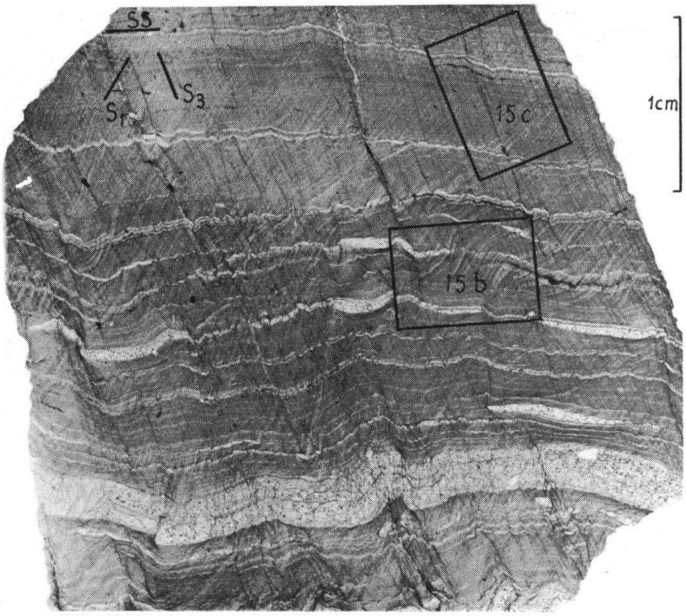


Fig. 15a Part of Sardic micro fold in thin section of Cabitza slate. Parallel to s_1 a tectonic banding resembling the bedding developed. Locality co-ord. 41,6 — 64,4. (2 ×)

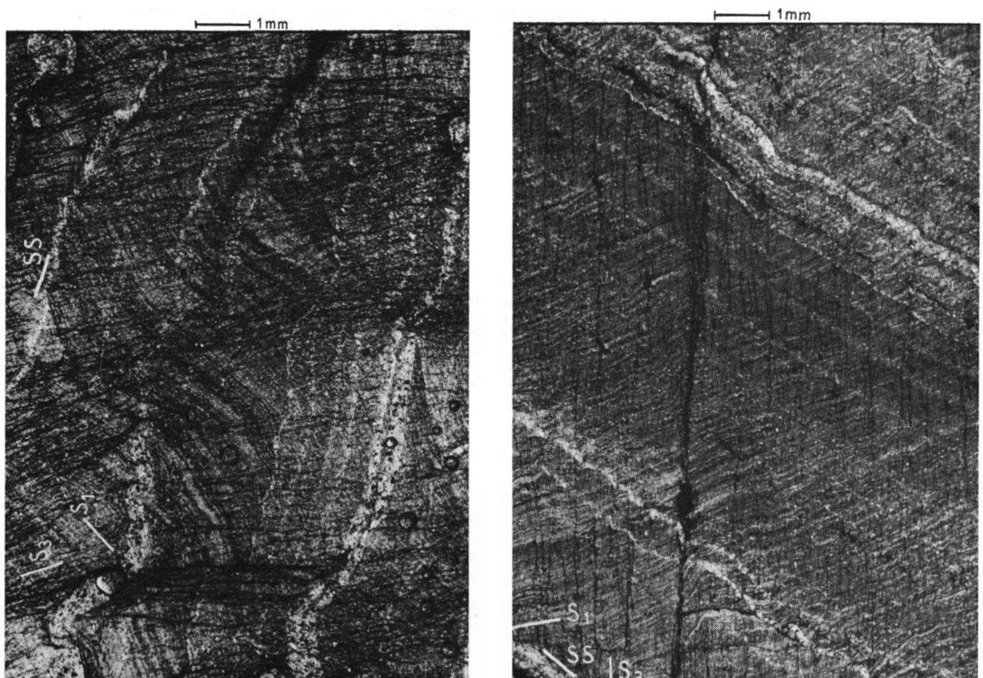


Fig. 15b and c Details of fig. a; ss, s_1 and s_3 in Cabitza slate.

case there is a possibility that the original bedding is completely erased. In that case we have to be very careful with our conclusions. If bedding, cleavage and tectonic banding occur together, there will be no problem in distinguishing them (fig. 15). If the first cleavage is oblique to a certain banding, we may assume, that this banding is a sedimentary one. In this part of Sardinia, however, the lamination, which is almost always seen in the Cabitza slates ("scisti listati"), represents a sedimentary layering. In both cases, s_1 parallel to ss and s_1 oblique to ss, the lamination or banding has the same appearance.

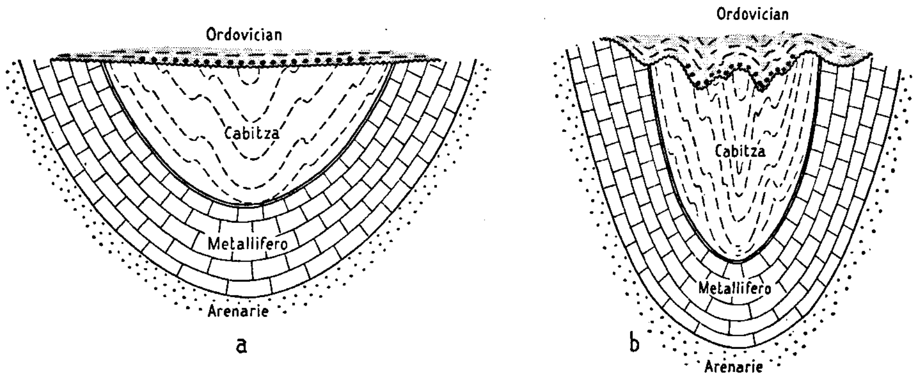


Fig. 16a Schematic N-S section through the Rosas-Terreseo syncline (E-W) after the Sardic phase and the deposition of the Ordovician sediments, but before the Hercynian deformations.
Fig. 16b Same section as fig. a, but after the second (E-W) folding phase.

SECOND FOLDING PHASE (FIRST HERCYNIAN PHASE)

The initial folding of the unconformable Ordovician rocks has the same direction as the Sardic folds (E-W), therefore this phase cannot be detected easily in the Cambrian rocks, as the main result was a further tightening of the large Sardic structures and no cross-folds developed (fig. 16b). The second folding is apparently disharmonic. The basal conglomerate beds of the Ordovician are strongly folded (almost always vertical), while the overlying slates are only moderately folded. The Cambrian rocks, already folded by the Sardic phase, were most probably only slightly deformed by the second phase. Consequently one may not simply subtract the E-W folding of the conglomerates from the folding of the Cabitza slates directly under the unconformity, to reconstruct the original orientation of the Cabitza beds. As a consequence of the disharmony of this folding the plane of unconformity became in many places a detachment horizon, along which some movement took place.

The first evidence of this folding occurs in rocks of Ordovician age, where it is clear that the beds were folded before the second Hercynian folding (N-S) took place. This is especially well visible in the basal conglomerate beds in the Rosas-Terreseo area and throughout the whole Iglesiente area, where these conglomerates occur. At these places the later N-S cleavage cuts perpendicularly through these E-W striking, steeply dipping layers (fig. 17).

It is a striking phenomenon, that the bedding in almost all conglomerate outcrops is steep to vertical, while the overlying slates of Ordovician and Silurian age are only gently folded by this phase (Testa and Sartori, 1917). In those places, where the basal conglomerate is absent from the Cambro-Ordovician transition (locality with co-ordinates 41,6 — 82,6), the contacts are barely inclined. It seems therefore, that this phenomenon is dependent upon the presence of the conglomerate.

The Ordovician and Silurian slates are folded in very gentle E-W striking folds with large wave-lengths and comparatively small amplitudes. They are best seen in the profiles. From the partial absence of E-W cleavage in the Ordovician and Silurian rocks of the area, connected with this folding, it is concluded that these are primarily concentric folds. At a few places, however, some E-W directed cleavage is connected with this phase (s_2). S_1 is the Cambrian Sardic phase cleavage and consequently lacks in the Ordivician rocks. Hence s_2 is the oldest present cleavage in the Ordovician rocks, but since s_2 is only locally developed the third phase cleavage (s_3) is normally the first cleavage of these rocks.

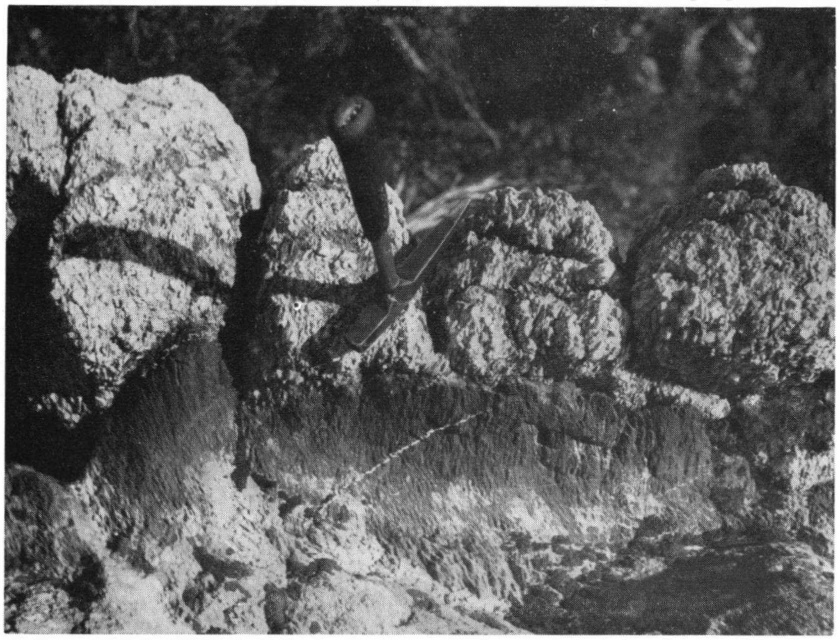


Fig. 17 N-S fracture cleavage (s_3) cross cutting through E-W striking, vertical dipping, conglomerates at Pta di Genna Pira (hammer stands vertical). Locality co-ord. 40,9 — 72,3.

The orientation of the intersection line of Ordovician ss and the s_3 cleavage plane, (δ_3), gives indication of the dip of the ss at the moment that s_3 originated. We have to be careful, however, and check if later deformation has refolded the rocks and consequently changed the original orientation of the δ_3-axes and, if this happened, we have to know in which way they are refolded before we make conclusions about the original orientation of the ss, as it was fixed after the second (E-W) folding phase. There is a possibility of reconstructing the original position of the δ_3-axes in those places where complex refolding took place, or even where creep disturbed its structural position. We therefore need a special feature, e.g. a recognizable plane or lineation of which we know the exact original position. In this case we have such a feature represented by the elongated pebbles of the conglomerate. The direction of the elongation axis in those outcrops throughout the whole area, where the influence of the fourth folding phase is limited or absent, is constant and almost vertical, and the elongation is caused by the same folding phase to which the s_3-planes, and consequently the δ_3-axes, belong. It is most probable, that this axis of elongation originated in an almost vertical attitude throughout the whole area (this will be discussed in the treatment of the third folding phase). The angles between the elongation axes and the δ_3-axes are therefore extremely important. In those places, where we find an angle of about 90°, we may assume that the elongation axis originated almost vertically in the s_3-planes, and hence the δ_3-axis was almost horizontal. We may now suppose, that the bedding in this place was almost horizontal before the third deformation took place and in as much as it was folded by the second folding phase we conclude, that we deal with an anticlinal or synclinal hinge of a fold belonging to this phase. From this one can conclude, that the smaller the angle

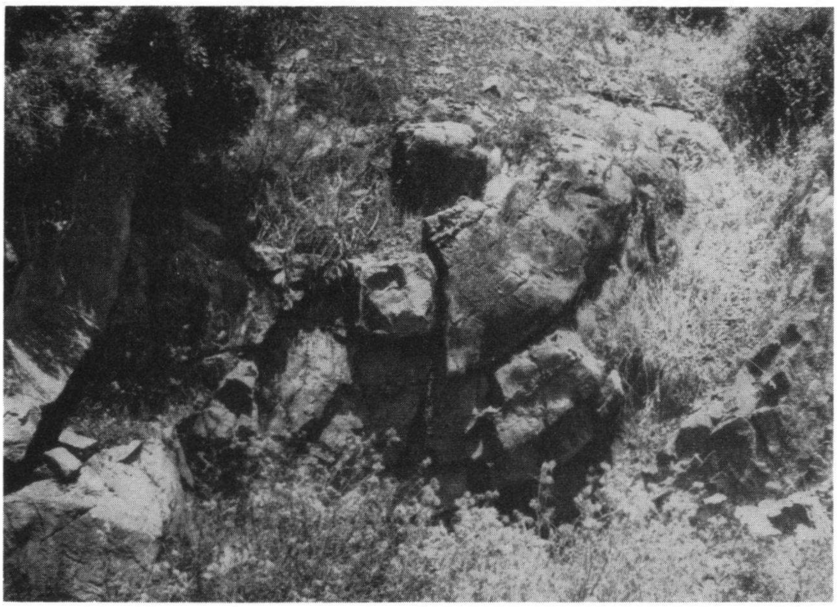


Fig. 18 Metallifero limestone folded by one of the first two E-W folding phases. Locality co-ord. 39,9 — 75,7.

is the steeper the bedding was. When we plot these angles on a map and connect measurements of the same value, we have the original strike. The lines, connecting the high angle (nearly 90°) values, thus give the original anticlinal and synclinal axes of the first Hercynian folds. As we are dependent on the conglomerates for the elongation axes, we are restricted to a few outcrops and as the δ_3-axis or the elongation axis is not visible in every conglomerate outcrop we are even more restricted.

In the conglomerates north of the village of Procaxius (co-ord. 36/37—70/71) one can measure many δ_3-axes. There is a good elongation direction of the pebbles measurable, especially in the largest N-S striking conglomerate band (about 10—30 m thick and 1 km long), and one can find the δ_3-axes too. In this conglomerate band, going from south to north, we find steep δ_3-axes (small angle elongation axis – $\delta_3$axis), less inclined δ_3-axes, horizontal δ_3-axes (almost 90° angle), more inclined δ_3-axes and steep δ_3-axes; thus forming a profile through an E-W fold belonging to the second deformation phase.

In theory this method is a most useful one, but it must be well understood, that such a method can only be used correctly in areas where many observations can be made. Above all the assumption, that the direction of the elongation is a fixed one, must be established. As the possibility to make these observations is restricted, the practical value of this method is small for this area.

When we look at the geological map we see almost in the centre of the mapped area an intricate pattern caused by cross folding. It is obvious, that the pattern is the result of an E-W folding and a N-S folding. As the folded rock is of Ordovician age, it is clear that the E-W folding does not belong to the Sardic phase, but to the first Hercynian deformation. The Mte di Genna Pira (co-ord. 39,8 — 72,2) consists of an E-W syncline of the second phase heavily refolded by the third folding (N-S). Some of these structures will be discussed in the treatment of the third phase.

In the north-eastern part of the mapped area we find rocks of Silurian and perhaps post-Silurian age. These rocks are gently folded along horizontal E-W axes. The wave-length of these folds is about 300 m and the amplitude is comparatively small.

The Ordovician rocks in the eastern part of the area are folded by the second folding phase, but later deformations disturbed many structures and a good deal of the structures are not detectable through the lack of recognizable bedding planes. One has the impression that the whole Ordovician area is gently folded by this phase, but as later deformations took place with almost the same direction it is extremely difficult to distinguish one from another.

It is very difficult to find minor folds belonging to one of the first two (E-W) folding phases. A nice example of such a fold is situated along the road immediately beneath the mess building of the Rosas mine (co-ord. 39,9 — 75,7; fig. 18). The fold axis of this folded Metallifero limestone sequence is horizontal and NW-SE directed. It is impossible to decide whether this fold belongs to the Sardic folding, or to the first Hercynian.

In the region north of Domusnovas (Iglesiente) the second folding phase seems to have cleavage folds with vertical cleavage and axial planes striking E-W (Arthaud, 1963).

THIRD FOLDING PHASE (HERCYNIAN MAIN PHASE)

The major Hercynian structures, trending N-S, are evident from the geological maps as well as in the field. These structures constitute the main phase, since they belong to the most intensive and extensive Hercynian folding. Such structures are well known throughout the whole Iglesiente area and Sulcis. As the Ordovician and Silurian rocks were folded by this phase, but Lower Permian rocks near Iglesias were obviously deposited afterwards, a Hercynian age can be assumed.

The formation of the major folds was accompanied by the production of a strong fracture and crenulation cleavage in almost all rocks (fig. 19) except in the limestone and dolomite. The major folds belonging to this phase are quite large, up to several kilometres wave-length and a few kilometres amplitude, but they are decidedly smaller than the major E-W Sardic structures, on which they are superimposed. The minor folds are mostly parasitic folds upon larger folds (fig. 26).

In order to facilitate the detailed description of the mapped area it has been divided in subareas (fig. 20). The structures of these subareas will be discussed below, beginning with the "Arenarie" subareas (subarea numbers 22, 23 and 24 in the south and 1 and 2 in the north) followed from west to east by the "Cabitza and Ordovician" subareas (subarea numbers 4—21, 25 and 26).

The anticline south of the large E-W Rosas-Terreseo syncline of Sardic age has been refolded in the Hercynian orogeny by N-S cross-folds. The cross-folding of an anticline by an anticline produces a dome, of which a number of excellent examples are known in this part of Sardinia, where the cores of Arenarie sandstone are surrounded by limestone and dolomite of the Metallifero Formation. The very large dome in Iglesiente for example is known as the "anello Metallifero". Poles to the bedding planes in subarea 22 (fig. 21, diagram 22) illustrate the form of the dome structure here. The plot of poles to the s_3 planes (fig. 22, diagram 22) demonstrate the essentially N-S orientation of the fold axis. However, the orientation of the intersections of the ss and s_3 planes (δ_3), plotted in fig. 23, diagram 22, is parallel

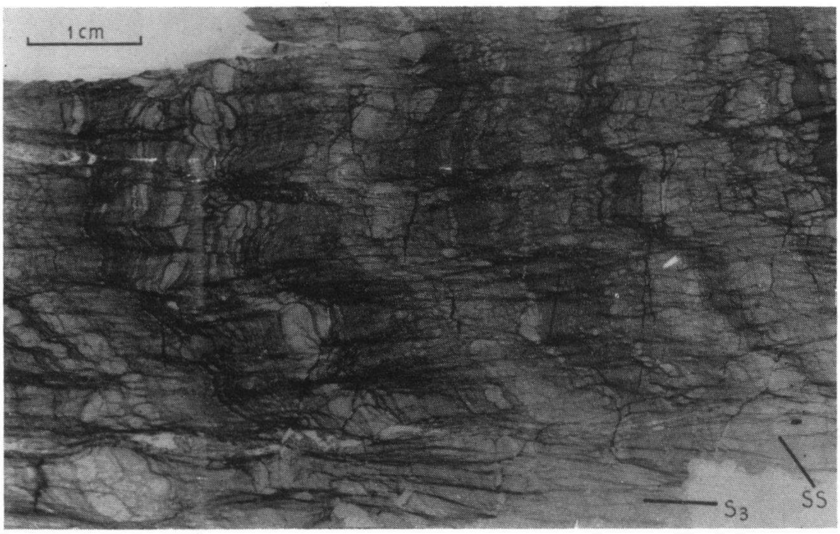


Fig. 19 Fracture and crenulation cleavage (s_3) of third folding phase in Cabitza slate. Locality co-ord. 42,1 — 65. (1,5 ×)

to the main axis of the N-S anticline, but the δ_3 axes are mostly plunging very steeply. The girdle corresponds to the form of the pre-existing E-W Sardic anticline, showing clearly how the rocks were deformed during the earlier folding. In the field one can map the exact position of the axial plane trace of the anticline of this subarea and this parallels the N-S cleavage. This axial plane does not form the symmetry plane of the whole anticlinal structure, which runs NW-SE (see map). Immediately west of this anticline a fault (co-ord. 40—63) with a probable thrust movement disturbed the northern part of the dome and is partly responsible for the asymmetry of the whole structure in comparison with the axial plane trace of our anticline.

In subarea 23 the s_3 is also well developed (fig. 22, diagram 23). The whole subarea is formed by Arenarie folded in a large anticline (see fig. 21, no 23). As it is a cleavage folding the axial plane parallels the s_3 and the fold axis the δ_3 (fig. 23, no 23), both striking north. Also here most of the δ_3 axes plunge very steep, but a partial girdle in the diagram is present. In the extreme north of this Arenarie anticline the s_3 fracture cleavage deviates from the N-S trend. Here the strike of the cleavage is NE-SW to ENE-WSW. This is not caused by later deformation, but originated in this position as we will see later on in this chapter. The eastern limb of this anticline is partly cut off by a N-S thrust fault, which also belongs to the Hercynian main folding.

In the third Arenarie anticline some kilometres to the east (subarea 24 of fig. 20) the fracture cleavage (s_3) is also well developed. Poles to the bedding planes and to the s_3 planes and intersections of these planes are plotted in diagrams, respectively fig. 21 no 24, fig. 22 no 24 and fig. 23 no 24. One sees immediately that the s_3 has a different orientation than in the previous two anticlines. There is a certain difference between the δ_3-diagrams of the subareas 22 and 23 and the δ_3-diagram of subarea 24. The first two diagrams show steeply plunging δ_3-maxima, while the latter shows a gently plunging one. Just as in the diagrams 22 and 23 of fig. 23, a certain girdle in diagram 24, indicating an earlier folding, is unmistakable, but from the gently plunging δ_3-maximum we may conclude that the previous folding here was only a very gentle one in contrast to the former two subareas. The s_3 in subarea 24 is regularly developed with a NE-SW strike. Apart from this different orientation the s_3 has exactly the same appearance as in the previous two Arenarie subareas. We see on the geological map that the axial plane trace parallels the s_3 and has therefore the same anomalous direction. This phenomenon will be discussed later on in this chapter. In the southern part of this subarea several smaller folds developed with axial plane fracture cleavages. These folds can be seen very well along the road, that runs N-S through this area (co-ord. 37,2 — 73,5; fig. 24).

The Arenarie north of the Rosas-Terreseo syncline was not severely affected by the N-S folding. One can see this on the map, where it is clear that the Sardic E-W structure is only slightly refolded and it is obvious in the field where N-S minor structures are almost lacking and cleavage of this phase (s_3) is rare.

S_3-planes, bedding planes and δ_3-axes of subarea 1 (fig. 20) are plotted respectively in diagram 1 of fig. 22, 1 of fig. 21, and 1 of fig. 23. The bedding plane diagram shows a girdle, representing a fold with s_3 as axial plane and δ_3 as a steep fold axis. As part of the layers are vertical and sometimes even slightly overturned (a phenomenon most probably caused by creep), one would interpret this diagram as a structure with an E-W axial plane; the map, however, clearly indicates an open fold with a N-S axial plane. The δ_3-axes plunge rather steeply as in the three southern Arenarie anticlines, which clearly shows that the beds were already folded with a steep dip, before the beginning of the third folding phase.

The s_3-planes of subarea 2, plotted in diagram 2 of fig. 22, are NE-SW striking. We observe here the same deviation from the N-S direction as in the easternmost Arenarie anticline south of the Rosas-Terreseo syncline (subarea 24; diagram 24, fig. 22). Outside these two subareas (1 and 2) s_3 is only barely developed in the Arenarie rocks of the large E-W (Sardic) anticline of which the subareas 1 and 2 form part, and neither minor nor major third phase structures can be found.

In the more fissile Cabitza slates a new crenulation cleavage accompanied by small folds was produced by the Hercynian main folding (fig. 25, 26 and 27). In the more quartzitic Cabitza layers, where the Sardic slaty cleavage (s_1) could not develop, the s_3 is a fracture cleavage.

The large area of outcropping Cabitza slates is divided in subareas (fig. 20 areas 4, 8, 9, 11, 13, 25 and 26), of which a diagram of poles to the ss-planes and a diagram of δ_3-axes has been made. As the s_3 is Hercynian it makes no difference whether we measure the s_3 in the Cabitza or in the Ordovician slates. Therefore another division in subareas for the s_3 is made.

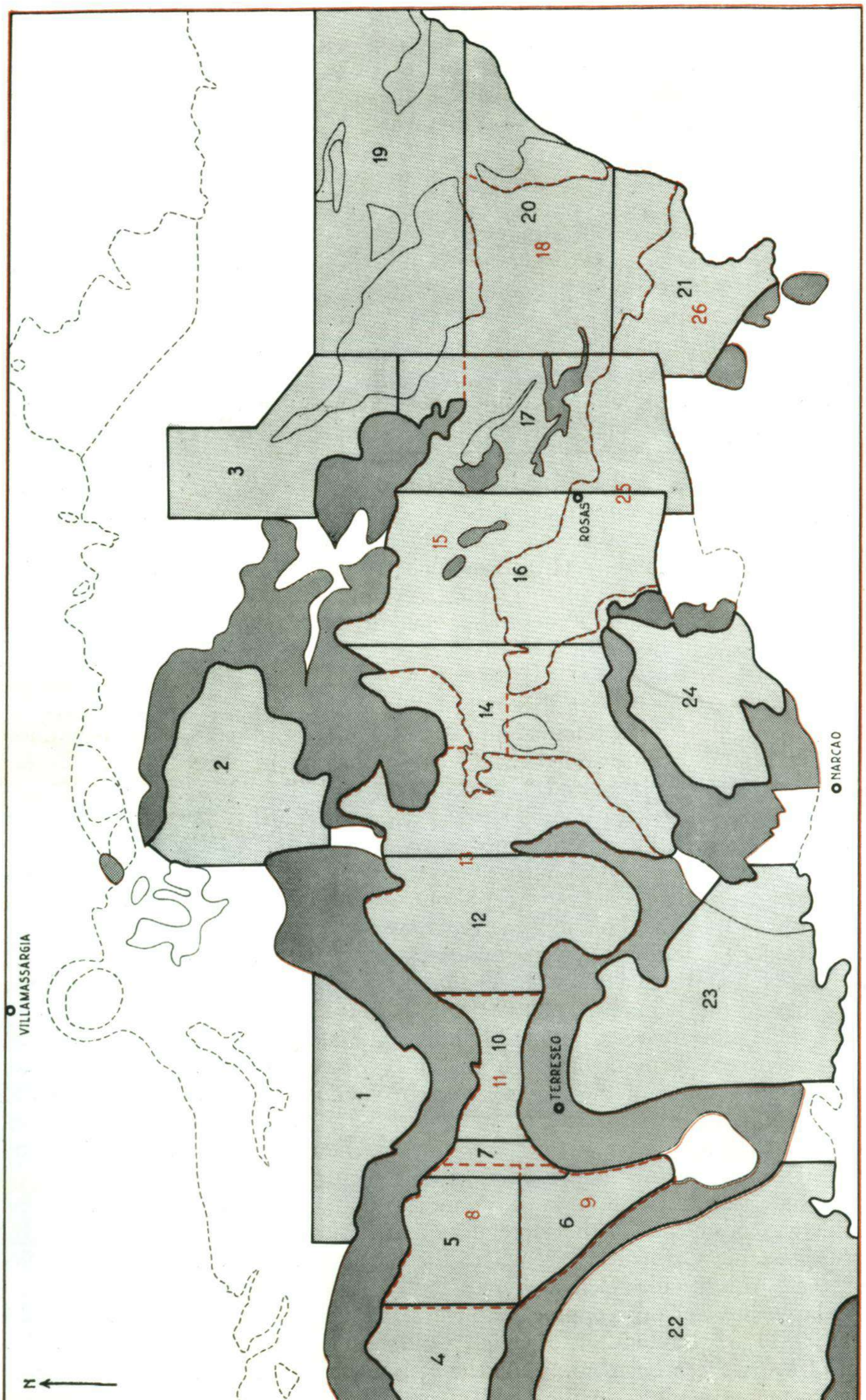


Fig. 20 Geological sketchmap of northern Sulcis showing the division in subareas used for the diagrams of fig. 21, 22 and 23.

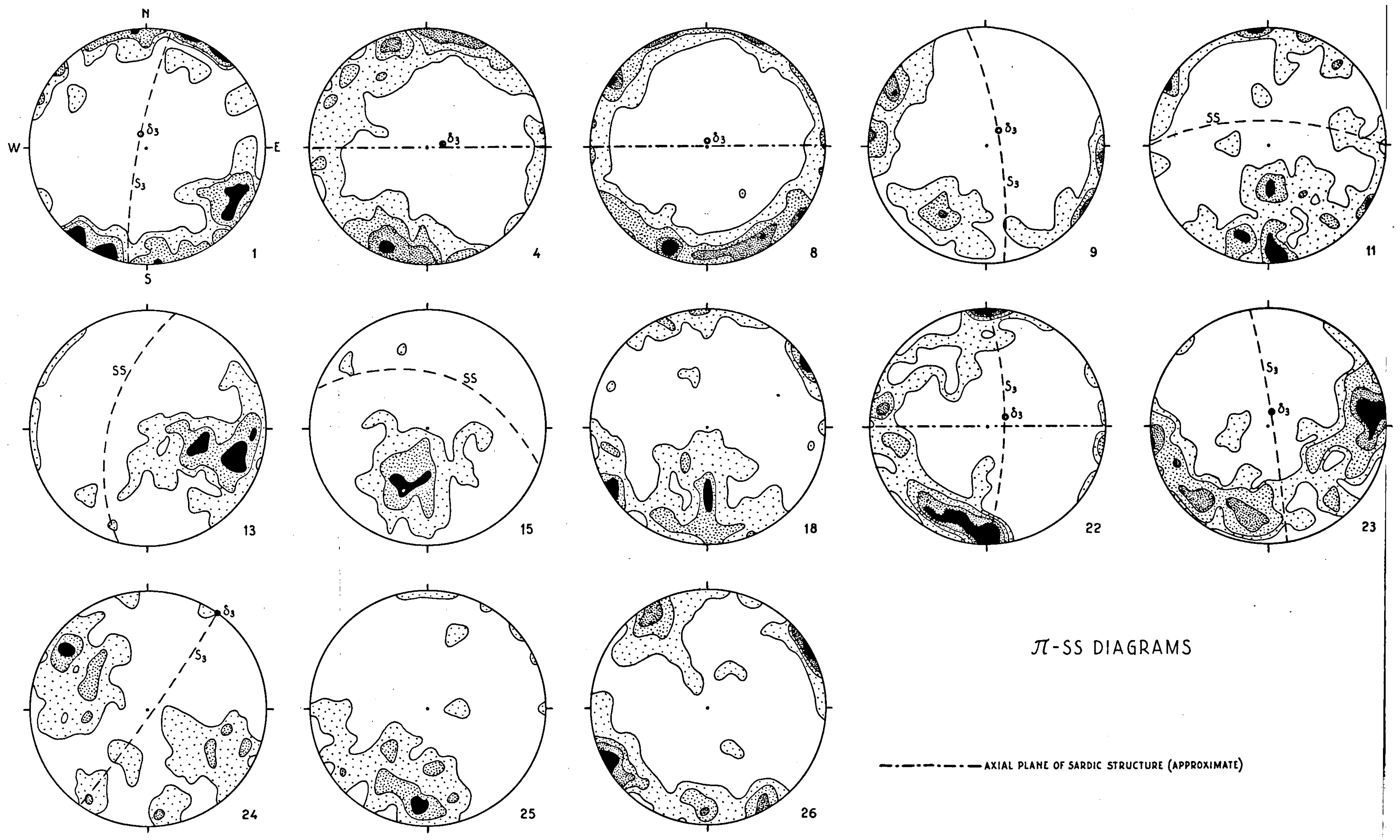
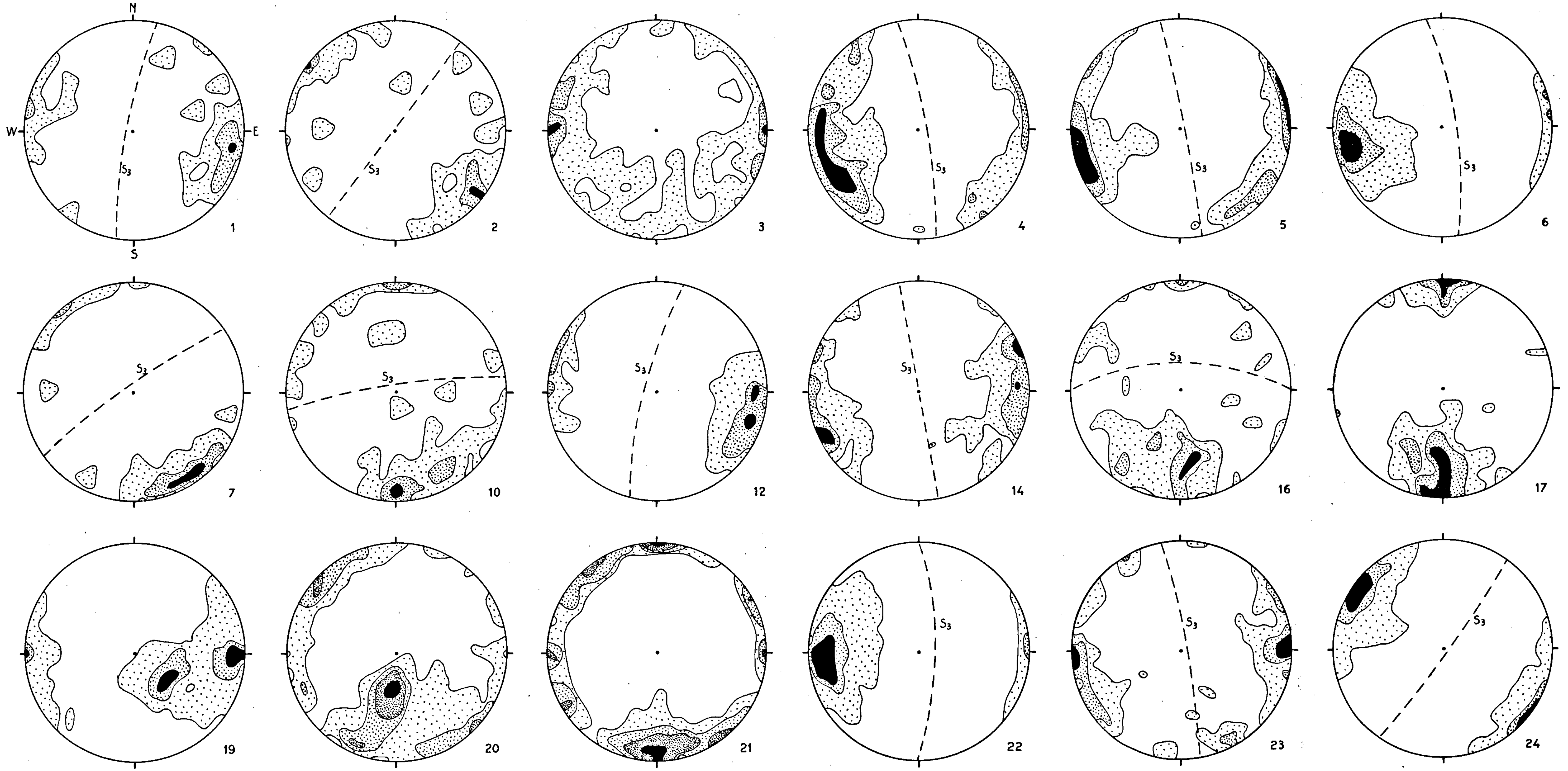


Fig. 21 Poles to the bedding planes (π-ss). The numbers of the diagrams correspond with the numbers of the subareas of fig. 20.

no	poles	contours in %	max. %
1	50	2—4—8	10
4	250	0,8—2,4—4,4—8,4	10
8	400	0,7—2,3—4,3—6,3	8,3
9	150	1,3—5,3—8,8	13
11	75	1,3—3,9—6,6	8
13	115	1,7—3,5—6	7
15	125	1,6—4,8—8,8	10,4
18	150	1,3—3,3—5,3	6
22	225	1,3—2,2—3,4—5,9	7
23	100	1—2—4—7	9
24	150	1,3—3,3—5,3	5,3
25	50	2—6—10	12
26	150	1,3—2,9—4,6—8,3	10,5

Fig. 22 Poles to cleavage planes of the third folding phase (π-s_3). The numbers of the diagrams correspond with the numbers of the subareas of fig. 20.

no	poles	contours in %	max. %
1	35	2,8—8,5—16,1	19,6
2	35	2,8—8,5—14,2	14,3
3	78	0,9—4,8—-9,9	11,5
4	200	1—3,5—6	8
5	300	1—3,6—9,9	12
6	165	1,3—6,8—12 8	16,4
7	50	2—10—18	22
10	50	2—8—16	22
12	110	1,7—7,1—11,7	14,4
14	115	1,7—4,3—6,9	8,7
16	100	2—4—6	7,5
17	100	2—4—6	7,5
19	250	1,2—4—6,4	7,6
20	300	1—2,3—3,6—7	8,6
21	250	1,2—4,4—7,6	10
22	200	1—5—10,5	14,2
23	130	1,5—4,6—7,7	10,7
24	120	0,8—7,5—15	21,6



π-S_3 DIAGRAMS

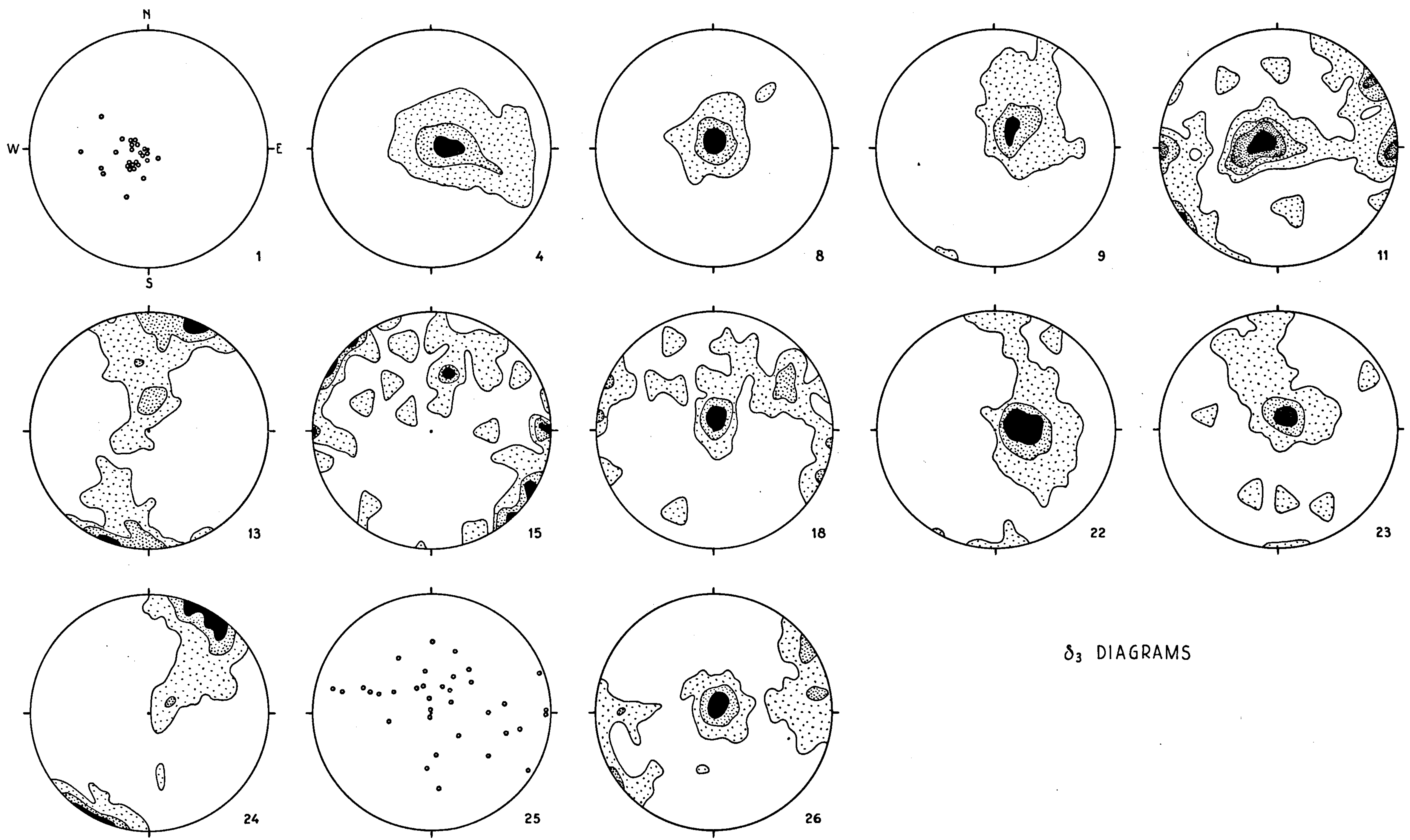


Fig. 23 Intersection lines of ss and s_3 (δ_3) and third phase fold axes. The numbers of the diagrams correspond with the numbers of the subareas of fig. 20.

no	δ_3-axes	contours in %	max. %
1	26	—	—
4	200	1—5,5—12	17,5
8	250	1,2—10—20	29
9	150	1,3—6,6—12,3	15,3
11	90	1,1—3,2—5,5—11	15,5
13	125	1,6—4—7,2	9,6
15	50	2—6—8	10
18	50	2—6—12	22
22	170	1,2—5,9—11,8	20,6
23	60	1,6—8,3—18,2	24,9
24	110	1,8—6,3—10,8	13,6
25	36	—	—
26	125	1,6—4,8—8,8	12

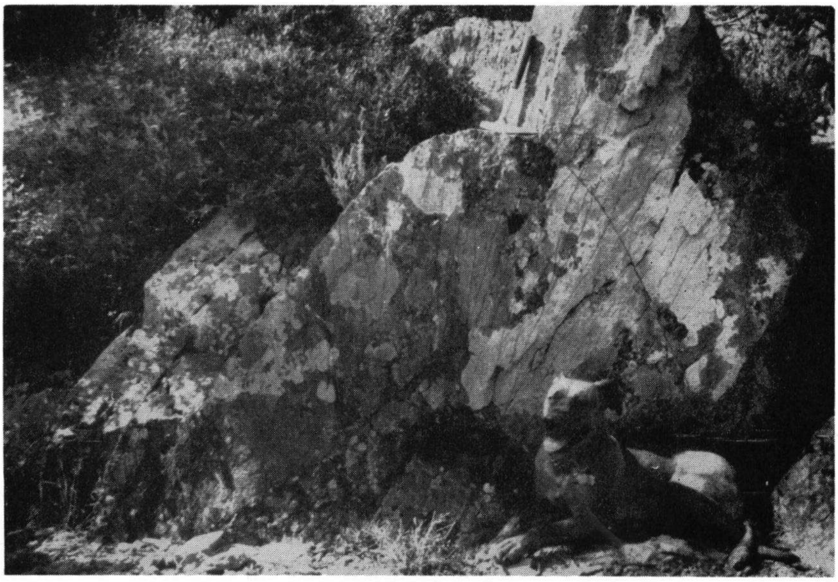


Fig. 24 Minor similar fold with axial plane fracture cleavage (s_3) in Arenarie sandstone. Locality co-ord. 37,4 — 73,4.

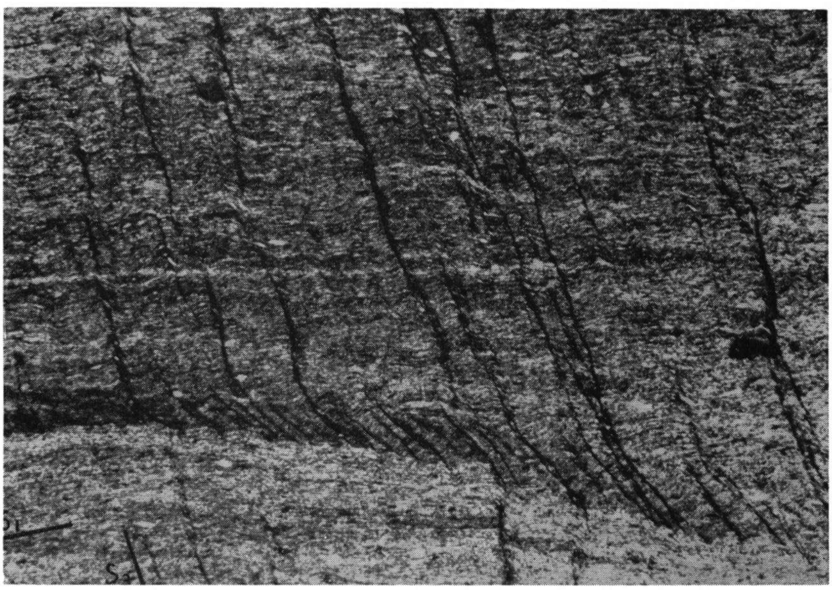


Fig. 25 Crenulation cleavage (s_3) of third folding phase. Locality co-ord. 39,4 — 76,1. (15 ×)

The s_3 is present everywhere in the subareas 4, 5 and 6. Many s_3-planes were measured and poles to them were plotted in the diagrams 4, 5 and 6 of fig. 22. Diagram 6 has the strongest maximum, but the diagrams 4 and 5 show fairly good maxima too. The s_3-planes, representing the maximum or average value of the various diagrams, have almost the same strike (near N-S) and dip. No major structures are made by this folding phase in the subareas 4 and 5. In the field, however, one can observe many minor structures; most of these minor folds have dimensions up to 10 cm, but larger folds up to 50 m do occur.

All the bedding planes in the subareas 4 and 8 dip steeply and the majority strike E-W in the Sardic trend, as shown in diagram 4 and 8 of fig. 21. The girdles

Fig. 26 Parasitic folds with axial plane fracture cleavage (s_3) in Cabitza slate. Locality co-ord. 40,8 — 70,1.

of these diagrams are formed by folding around steep foldaxes (diagrams 4 and 8 of fig. 23) resulting in numerous minor folds.

In subarea 6 one can see a major structure on the map. The whole subarea is formed by a syncline, showed clearly by the Metallifero limestone and dolomite, which surround this subarea. Poles to the bedding planes, s_3-planes and intersections are plotted in diagrams, respectively fig. 21 no 9, fig. 22 no 6 and fig. 23 no 9. Diagram 9 (fig. 21) shows a girdle representing a fold with a somewhat overturned eastern limb. In this diagram s_3 and δ_3 (representing the maxima of the corresponding diagrams of this area) are indicated as they represent respectively axial plane and

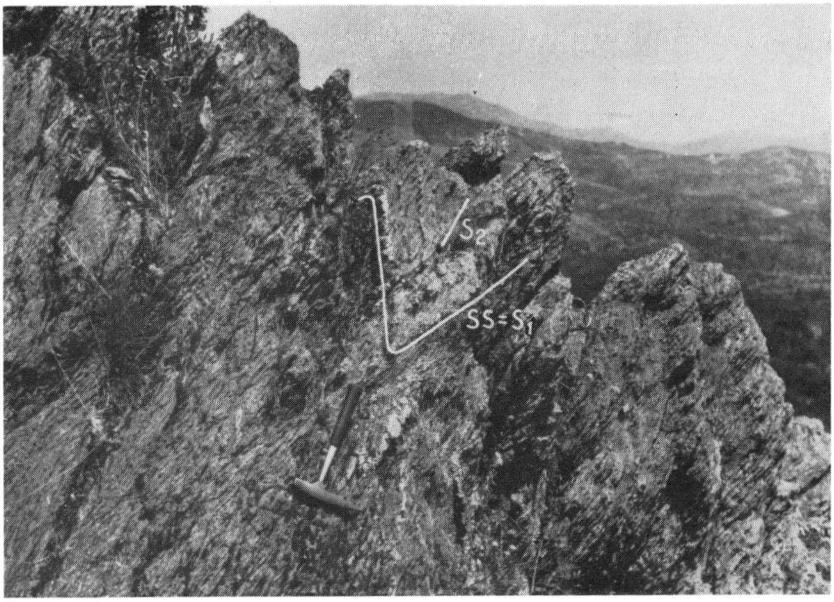


Fig. 27 Minor folds with sharp hinges and axial plane fracture cleavage (s_3) in Cabitza slate. Locality co-ord. 41,6 — 72,6.

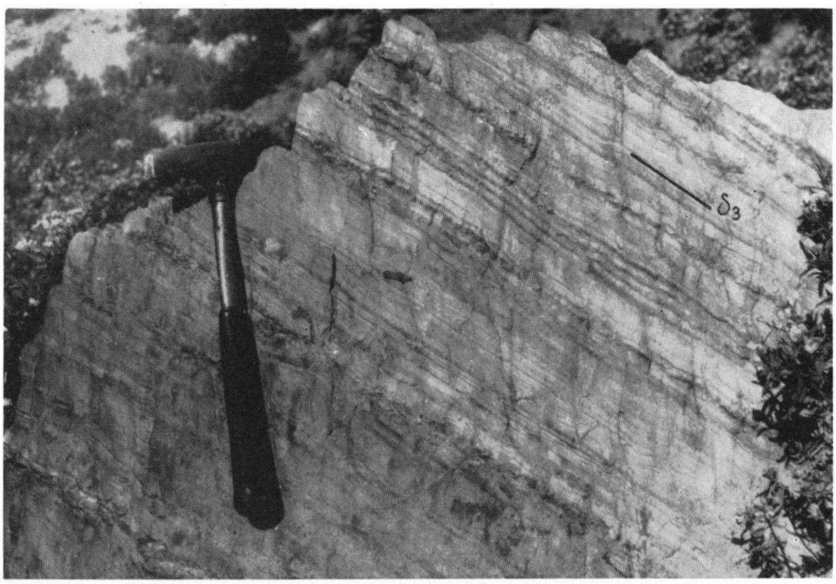


Fig. 28 Gently plunging δ_3-axes seen on the s_3 fracture cleavage planes. Locality co-ord. 40,7 — 68,2.

fold axis. In the field the axial plane trace can be mapped accurately, while the curvature of the hinge zone is rather sharp.

Subarea 7 is a narrow zone less extensive than the other subareas, but extremely important. In this narrow zone one can observe that the strike of the s_3-planes, which is N-S (N 10° W) in the subareas 5 and 6, gradually turns to E-W. In fig. 22 no 7 poles to the s_3-planes are plotted. One sees a somewhat elongated maximum, indicating that the strike of the cleavage planes varies from NNE to ENE with steep to vertical dip. In the field the changing of the strike direction is obvious although gradual through a transition zone about half a kilometre wide. In subarea 10 the s_3 strikes almost E-W. The s_3 in this area is not so abundant and not so regularly developed, but the observed cleavage planes are obviously the continuation of the cleavage planes of the western area. Following these s_3-planes to the east one sees the same phenomenon. The cleavage turns back to the N-S orientation (see fig. 22 no 12). The transition zone here is smaller and irregular and therefore has not been separated as a subarea.

In fig. 23 diagram 11 another important feature is illustrated; namely that the plunge of most of the δ_3-axes remains steep. As later folding barely occurs in this area, this indicates that here too the rocks were folded by earlier folding and that this cleavage belongs to a later folding than the E-W structure. Not all the δ_3-axes in this subarea plunge steeply (fig. 28). This can be explained easily. Since s_3 strikes almost E-W in this particular area, the angle between ss and s_3 is very small. Sometimes the strike of the planes is parallel or the planes are parallel. In the first case the intersection (δ_3) is horizontal and in the second case no intersection occurs.

The structure thus formed by the cleavage (N-S turning to E-W, returning to N-S) is a rather large and unusual one. For the explanation of such a structure one has the choice between two possibilities:

1. the structure is simultaneous with the forming of s_3, or
2. the structure is caused by later deformation of an originally N-S s_3 structure.

In most of the cases where one has to explain this kind of structures, one can prove that a later deformation is responsible for the form of the structure. In this case, however, it is certain that this structure originated in this form, because within a relatively small area (subareas 8 and 11) the bedding planes are all parallel, demonstrating that the beds have not been differentially folded. Yet the fracture cleavage s_3, which is vertical everywhere, strikes N-S in subarea 5, swinging gradually in subarea 7 until the s_3 is almost E-W and parallel to ss in subarea 10. To the east of subarea 10 the angle between ss and s_3 increases again. Since the strike of s_3 is the only factor to vary through these subareas, it is clear that this characteristic structure is original, having its cause during the deformation of the third folding phase.

How can we explain the originating of such a peculiar structure without getting in trouble with some general rules? These rules say, that:

1. cleavage planes, formed under certain stress conditions during a folding phase, are normally supposed to originate as parallel or subparallel planes, mostly perpendicular to the largest principal stress, and
2. a stress, applied to a certain complex of rocks, will usually have the same direction throughout the whole complex.

If we stick to the letter of these rules we cannot explain the structure mentioned above, however, there are several exceptions to these rules. Cleavage is not always formed perpendicular to the largest stress (e.g. the conjugate system of the fourth phase), but this type of cleavage (s_3), with one set of planes along which (in principle) no movement took place, is. Principle 2 goes as far as it concerns homogeneous rocks. In this case, however, the complex of rocks is far from homogeneous. The greatest difference in physical properties lies between the rocks of the Arenarie and Metallifero Formation at one side and the rocks of the Cabitza Formation and the Ordovician rocks at the other. A stress applied to this complex of rocks will cause major structures of the massive rocks (Metallifero and Arenarie) to which the Cabitza and Ordovician slates have to adapt themselves. After the E-W folding phases the rocks were folded in large E-W synclines and anticlines with rather steep dipping limbs (large amplitudes). The third deformation (N-S) came with its largest principal stress E-W directed. The limbs of the large E-W Rosas-Terreseo syncline were folded. By this folding the E-W structure shortened considerably. West of Terreseo the southern limb of the E-W syncline folded outwards and consequently the limb immediately east of Terreseo folded inwards. Outwards in the meaning of opening and inwards a further tightening of the E-W syncline. This last movement is important for the deviating cleavage structure. The northern limb of the E-W syncline also folded under the E-W compression and by chance the part of the limb just

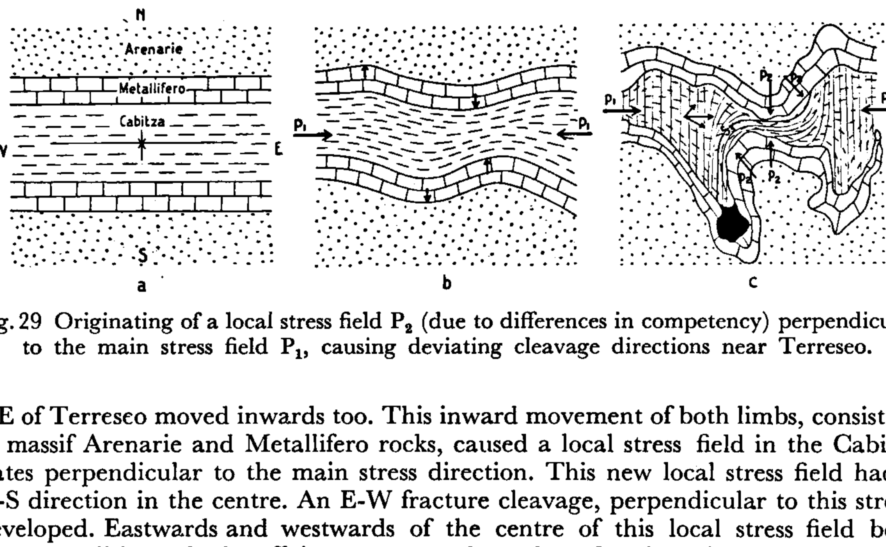


Fig. 29 Originating of a local stress field P_2 (due to differences in competency) perpendicular to the main stress field P_1, causing deviating cleavage directions near Terreseo.

NE of Terreseo moved inwards too. This inward movement of both limbs, consisting of massif Arenarie and Metallifero rocks, caused a local stress field in the Cabitza slates perpendicular to the main stress direction. This new local stress field had a N-S direction in the centre. An E-W fracture cleavage, perpendicular to this stress, developed. Eastwards and westwards of the centre of this local stress field both stress conditions shade off into one another, thus forming cleavages gradually swinging in orientation, until further to the east and to the west no influence of the local stress is met with and the cleavage was formed under main stress conditions and originated with a N-S direction (see fig. 29).

East of this "bottleneck" area not only the s_3-planes, but the bedding planes also, strike N-S. Diagram 13 of fig. 21 is a π-ss diagram of subarea 13. This area is strongly folded with s_3 parallel to the axial plane and δ_3 parallel to the fold axis (see respectively fig. 22 no 12 and fig. 23 no 13). As there is a maximum and almost no girdle in diagram 13 of fig. 21, we can deduce that the folding is isoclinal with sharpe hinges and slightly overturned. It is not easy to map these folds in the field by tracing the bedding planes or looking for fold hinges. It is better to use here the interpretation method of the cleavage (s_3)-bedding relation (fig. 36), to establish anticlinal and synclinal structures. Some of the axial plane traces of these folds are indicated on the map. Although a partial girdle is present in diagram 13 of fig. 23, the maximum represents almost horizontal fold axes. The conclusion is that this area was only gently folded by the previous two E-W folding phases.

Subarea 14 is the easternmost area in which the s_3 has a regular N-S strike. In the subareas 16, 17, 20 and 21 the stike of the s_3 is rather NE-SW to E-W than N-S. We have seen before that the s_3 in the Arenarie anticline (subarea 24) south of these subareas is regularly developed with a NE-SW strike. As little or no refolding occurred in these Arenarie rocks, it is obvious that later refolding is not responsible for this deviating direction. Starting from this statement it seems reasonable that the cleavage (s_3) here originated with a NE-SW to E-W strike. Sometimes s_3 dips with a low angle to NW and consequently the folds with s_3 as axial plane are overturned, which is very well seen along the railway near Campanasissa (fig. 30). Refolding in these subareas by the fourth deformation obscured the original orientation of the s_3 cleavage planes.

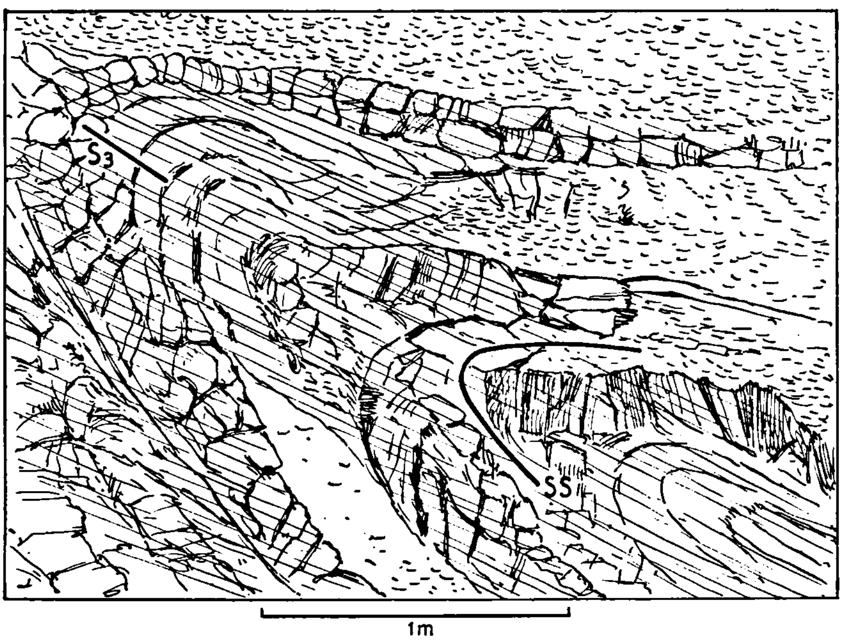


Fig. 30 Overturned fold of the third folding phase with axial plane fracture cleavage (s_3). The axial plane strikes NE-SW and dips NW. Locality co-ord. 41,4 — 82,3. (after photograph)

A narrow zone of folding and faulting occurs approximately along the N-S co-ordinate 71 (see map and fig. 1). In the south a fault brought the older Cambrian rocks (Arenarie) against Ordovician rocks. This thrust-fault has most probably a throw of at least 750 m. Following this thrust-fault northwards the throw decreases, until after about 2 km the fault merges into a sharp fold. The Metallifero limestones are folded upwards, forming a finger-shaped structure on the map. Further north two small outcrops of "calcescisti" occur in the Cabitza slates. These two outcrops form parts of older E-W anticlinal ridges, upfolded by the N-S folding of the third deformation phase. Northwards this steep anticlinal ridge merges into a fault zone, that cuts off the Metallifero and brings Arenarie sandstones against Cabitza slates. This fault here originated as a sharp fold, that broke through. The locality with co-ordinates 42,2 — 71,2 is the only place in the whole mapped area where Cabitza rocks lie against Arenarie rocks. We see on the map a N-S structure in this area (anticline, of which the western limb is cut off by a fault) formed by a remarkable thin Metallifero sequence (co-ord. 42,2 — 71,2). The thinness of the Metallifero here is probably determined by restricted sedimentation and partly caused by drawing out under tectonic conditions. The apparent "thickness" of the Metallifero immediately east and west of this structure is caused by E-W folds (see profiles). It is not possible to trace the large fold and fault zone (co-ord. 71) further northwards, but it seems probable, that it continues for many kilometres and there are indications that one can trace this zone back in the Domusnovas area. Why is this narrow N-S zone more intensively deformed by this third folding phase? We

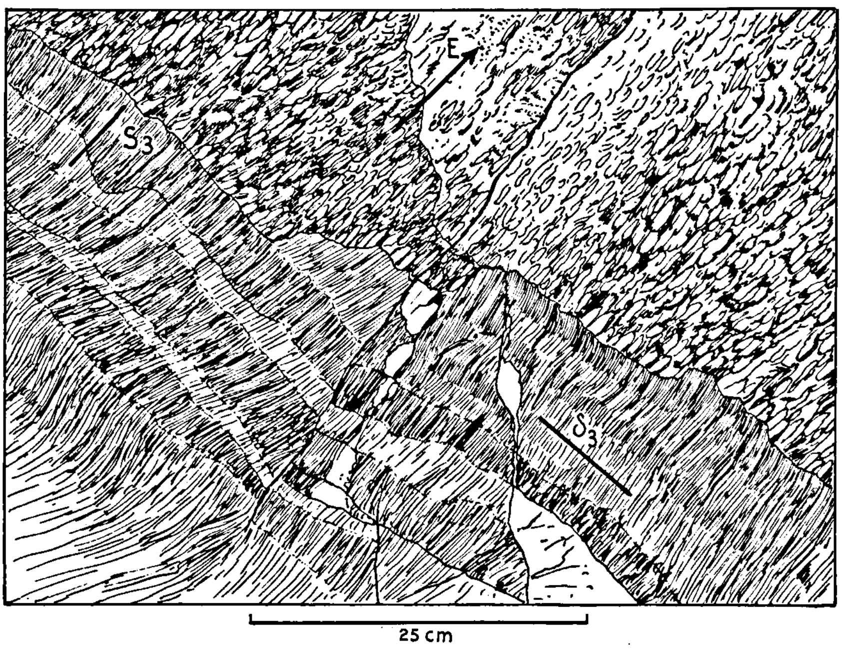
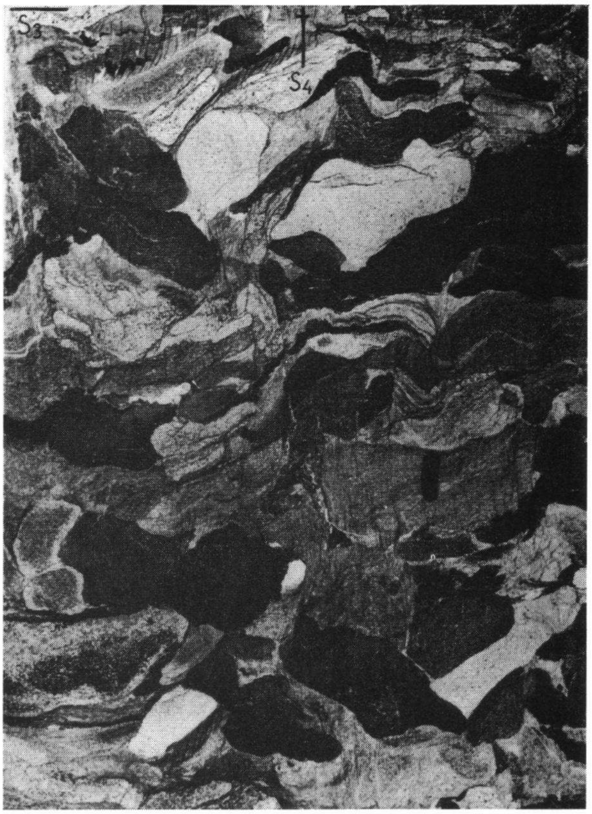
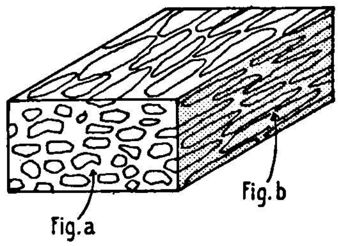


Fig. 31 δ_3 axes and elongation direction (E) of conglomerate pebbles perpendicular to each other, seen almost perpendicular to the s_3 fracture cleavage. Locality co-ord. 41 — 72,3. (after photograph)

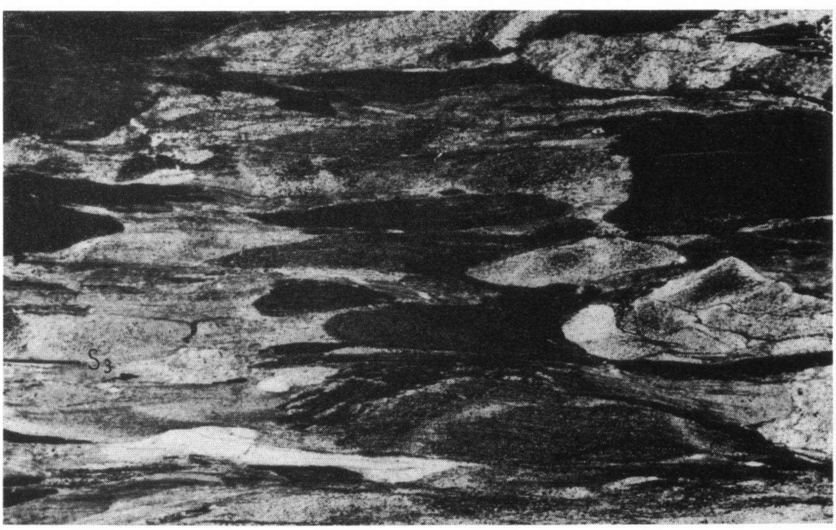
may assume, that the tectonic conditions were equal throughout the area. Hence the only explanation for the different behaviour of this narrow zone to the stress of the third phase is, that this zone was less resistant against deformation. This lower resistance was most probably due to a thinner sequence of the sediments, as is shown by the Metallifero in the north.

The eastern part of the area is almost completely covered by Ordovician rocks, but at several places the Cabitza is revealed by erosion. In the area north of Rosas (see geological map, scale 1 : 10000) the outcropping Metallifero limestone forms "islands" in the Ordovician slates. The Ordovician lies directly upon the Metallifero. The third phase refolded the WNW-ESE directed Metallifero ridges, thus forming dome and basin structures. As many contacts between Ordovician and Metallifero





a



b

Fig. 32 Deformed micro conglomerate with pebbles elongated in s_3. a. section perpendicular to the elongation and s_3 b. section parallel to the elongation and perpendicular to s_3. Locality co-ord. 36,9 — 70,7. (4 ×)

rocks are partly fault contacts, a certain upthrust caused by the second folding is probable.

As in many cases the third phase structures in the eastern part of the area are almost E-W and the intensity of this folding differs from place to place with s_3 not everywhere developed, it is sometimes very difficult to establish to which folding phase certain structures or s-planes belong. In the small area formed by the co-ordinates 44/45—76/77 some very clear N-S structures with a strong axial plane cleavage have been formed by the third folding phase. Several synclines and anticlines can be detected, if one makes use of the interpretation method (see fig. 36) of ss-s_3 relations.

An interesting feature belonging to the internal deformation of the third phase is the flattening and elongation of the pebbles of the Ordovician conglomerate, as already observed by Novarese (1914) in Iglesiente. He described the N-S cleavage cutting perpendicular through the basal conglomerates, producing a cracking and

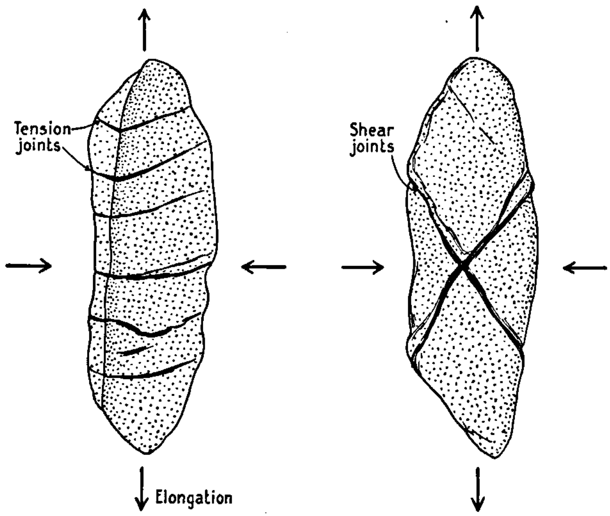


Fig. 33 Tension and shear joints in conglomerate pebbles caused by the third phase deformation.

squeezing out of the pebbles. In spite of this clear observation and the fact that a good recognizable s_3 is almost always present, Teichmüller (1931, p. 15) stated that cleavage fails in the conglomerate. This conglomerate, as we have seen in the chapter on stratigraphy, consists of two different types, both belonging to the base of the Ordovician deposits. These two types are:

a. conglomerate of slate fragments (purple coloured), and
b. conglomerate of quartz pebbles (white coloured).

We may not assume, that the pebbles of the first type were well rounded by the deposition. A certain elongation parallel to the bedding plane is probable for this type. The quartz pebbles of the second type, however, were most probably well rounded by deposition. In Sulcis one can observe many outcrops of both types of conglomerate where the longest axes of the pebbles are not always parallel with the bedding plane and in many cases even perpendicular to it (fig. 31). The conglomerate pebbles are flattened in a direction perpendicular to the s_3 and this flattening is compensated by stretching in a near vertical direction (fig. 32 a and b). Sometimes tension and shear joints developed during the deformation in the more competent pebbles (fig. 33). In some outcrops of the conglomerate of the first type the slate fragments are rather large (up to 15 cm) and flat. In these outcrops the longest axes of the pebbles are still parallel to the bedding plane. The pebbles, however, are obviously elongated in a near vertical direction, which is indicated by the median axes of these pebbles. This feature is very well visible in Iglesiente in the very thick conglomerate deposits between Nebida and Gonnesa and in some outcrops in Sulcis. There are several outcrops of the conglomerate where no deformation of the pebbles is seen. But, if a certain deformation is observable, one can ascertain that irrespective of the attitude of the bedding the elongation axes of the pebbles have the same direction.

Beside the deformed and elongated pebbles of the conglomerate there is another phenomenon in the Ordovician slates that shows this special kind of deformation, on which we can measure the elongation axis. This is presented by the green-

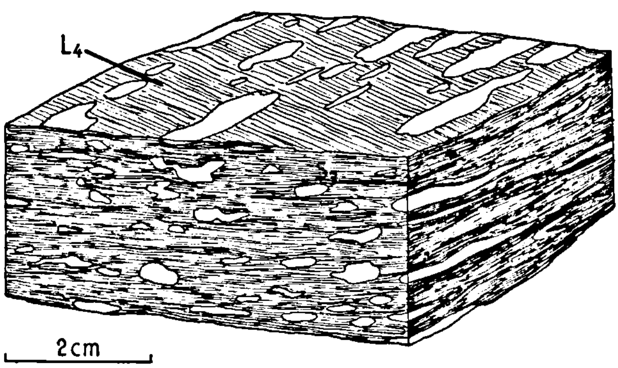


Fig. 34 Reduction spots deformed by the third phase into long stretched bodies parallel to s_3. L_4 is intersection of s_4 and s_3. Locality co-ord. 39,2 — 76,2.

ish reduction spots in the purple coloured slates of Ordovician age, deposited immediately after the conglomerate. These reduction spots were developed as a spherical halo around a nucleus, probably a tiny pyrite crystal, of which nothing is left. These spheres have been deformed to ellipsoids and sometimes even to long stretched bodies (fig. 34). As the longest and the median axes of these ellipsoids and of the elongated conglomerate pebbles lie in the s_3-plane and the longest axes of spots and pebbles have the same direction, it is obvious that it concerns a similar phenomenon formed during the same deformation (third folding phase).

E. Cloos (1947) described deformed oölites and since then several observations on this subject were made. An oölitic limestone forms an ideal subject for the study of internal deformation as both oölite and matrix have the same composition and as oölites are formed as spheres. In the top of the Arenarie Formation small oölitic limestones sometimes occur in Sulcis and Iglesiente. The few oölitic limestones found near Cse Procaxius and near Bingixedda (resp. co-ord. 36,3 — 70,1 and 36,2 — 66,2) do not show this distortion phenomenon well. South of the investigated area near Giba (co-ord. 23,5 — 70,4), however, deformed oölites occur

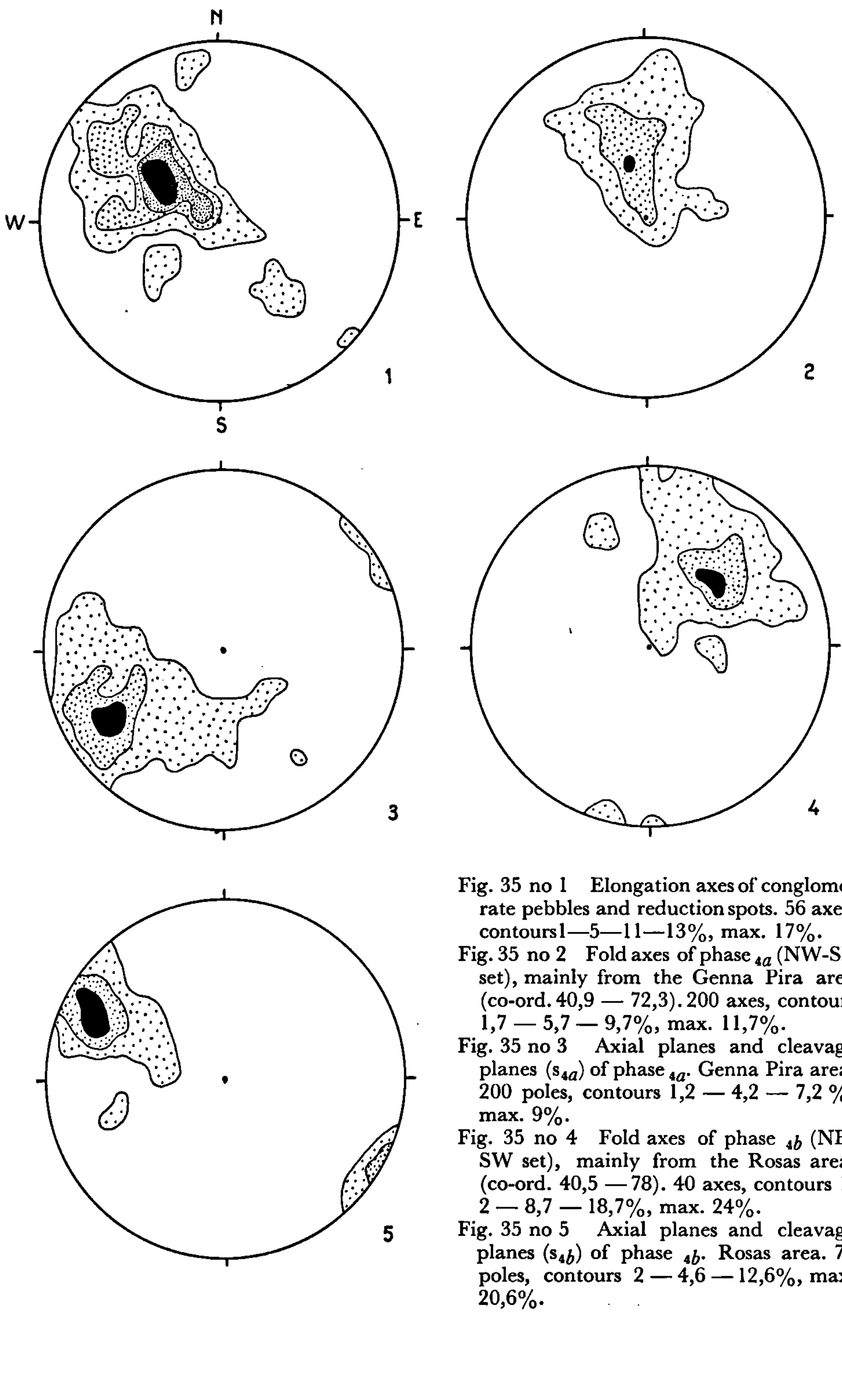


Fig. 35 no 1 Elongation axes of conglomerate pebbles and reduction spots. 56 axes, contours 1—5—11—13%, max. 17%.

Fig. 35 no 2 Fold axes of phase $_{4a}$ (NW-SE set), mainly from the Genna Pira area (co-ord. 40,9 — 72,3). 200 axes, contours 1,7 — 5,7 — 9,7%, max. 11,7%.

Fig. 35 no 3 Axial planes and cleavage planes (s_{4a}) of phase $_{4a}$. Genna Pira area, 200 poles, contours 1,2 — 4,2 — 7,2 %, max. 9%.

Fig. 35 no 4 Fold axes of phase $_{4b}$ (NE-SW set), mainly from the Rosas area. (co-ord. 40,5 — 78). 40 axes, contours 1, 2 — 8,7 — 18,7%, max. 24%.

Fig. 35 no 5 Axial planes and cleavage planes (s_{4b}) of phase $_{4b}$. Rosas area. 75 poles, contours 2 — 4,6 — 12,6%, max. 20,6%.

(Cosijn, 1965). Just as the flattening and elongation of the conglomerate pebbles and reduction spots in northern Sulcis the deformation in that area is due to the third folding phase (N-S).

Elongation axes of deformed pebbles and reduction spots are plotted in a diagram (fig. 35 no 1), which shows a good maximum with a steep direction and plunge (average 290°—60°) As is explained in the introduction of this chapter it is difficult to speak of a, b or c tectonic axes, if earlier deformations occurred. Therefore we cannot speak of a conglomerate elongated in the a- or in the b-direction. We may compare, however, our deformation with the hypothetical strain ellipsoid of the third phase. The largest principal stress of this phase is E-W directed and this is therefore the direction of the C-axis (shortest axis) of the ellipsoid. The A- and the B-axes are situated in the s_3-plane with B horizontal and A vertical in the direction of the elongation. As almost all measured elongation axes of pebbles and spots are steep, we can say that the deformation is in A (referring to the strain ellipsoid of this phase).

The first three folding phases together have caused the typical "Schlingenbau" of the Iglesiente and Sulcis areas. A special feature of the interference of the different fold directions are the dome and basin structures. Beautiful examples of such domes or "eyed folds" occur south of the Pta di Genna Pira (where a large one has a diameter of about 500 m, co-ord. 40 — 72,8). This structure is not only caused by uneven erosion through a thin blanket of Ordovician deposits, as we sometimes see in the eastern part of the mapped area, but by normal erosion of an upfolded older E-W anticlinal ridge. This is obvious in the field, where the core of this structure formed by Cabitza slate rises above the surrounding Ordovician conglomerate and slate. One can examine this structure better in the north than in the south, while the northern part of the structure is surrounded by well layered, steeply dipping conglomerates and in the south these conglomerates are absent and the Ordovician slates are poorly layered. One kilometre to the east we have almost the same kind of structure (co-ord. 40 — 73,7). The only difference is that this structure on the map is not completely surrounded by Ordovician rocks. This structure is, like the western dome, almost bordered by steeply dipping conglomerates. Between these two structures a very small outcrop of Cabitza slates is found, indicating another "eyed fold". At the Pta di Genna Pira (co-ord. 39,8 — 72,2) several strangely shaped structures, formed by the cross folding, are exposed.

Normally one has to know the correct stratigraphic subdivision before one starts a structural analysis of an area. In Sulcis, however, no paleontologic evidence can be found, but there is good structural evidence to establish the stratigraphic sequence of the Cambrian formations. The three Arenarie anticlines south of the large E-W Rosas-Terreseo syncline (subareas 22, 23 and 24) were formed by the third folding phase. These anticlines are large cleavage folds with s_3 parallel to the axial plane and in the fold limbs the strike of s_3 and ss are subparallel. The dip relations of s_3 and ss in the limbs are important indications of the direction in which the synclinal or anticlinal axis may be found from the outcrop. If we start in the field from Metallifero rocks east or west of the granite stock of M. s'Orcu and walk approximately along the E-W co-ordinate 38 eastwards or westwards into the Arenarie areas, we can observe in nearly every outcrop that we are nearing the anticlinal axis (better the axial plane trace) of the large N-S structure. After a certain distance we will pass the hinge of the structure, which is not directly visible in the field, but which is observable with the method mentioned above and proceeding to the Metallifero, which forms the other limb of the structure, we move away from the axial plane trace (fig. 36). The three structures are proved to be anticlines and consequently the Arenarie is older than the Metallifero.

As we can see in the diagrams of fig. 22, the s_3 has a rather steep to vertical dip in this part of Sulcis. In the south-eastern part of Sulcis s_3 has normally the same attitude. The same applies to the dip of s_3 in the western part of the Iglesiente area. However, in the eastern part of Iglesiente this cleavage is not developed as a vertical plane, but dips about 60° to the east (Arthaud, 1963).

The third folding phase is one of the most important and regularly developed deformations in both Sulcis and Iglesiente (Hercynian main folding). S_3 is developed in almost all outcrops of Lower Palaeozoic rocks. It is therefore worth to examen several examples of deformation caused by this phase:

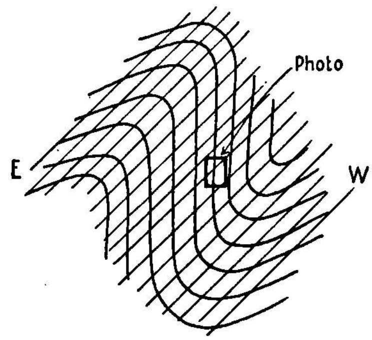


Fig. 36 Cleavage (s_3) — bedding relation in folded Arenarie rocks indicating that this outcrop is situated on the western flank of an anticline. Photo taken from N to S. Locality co-ord. 37,8 — 64,8.

In the field one can find good examples of tectonic banding parallel to s_3. Several examples of tectonic banding perpendicular to ss are arranged in successive stages of deformation (figs. 37a, b, c and d). On a smaller scale (thin section) this banding is even more spectacular (fig. 38a and b). It is clear that the phenomenon of tectonic banding is based on the principle of material transport. The dark zones parallel to s_3 consists of an accumulation of sericite, while the lighter coloured zones are made up of quartz.

A special feature of this Hercynian main folding phase, found especially in the Cabitza slates, are the small and regularly developed folds. At first sight one easily mistakes a bedding plane folded in this way for ripple marks (fig. 39a). In the cross

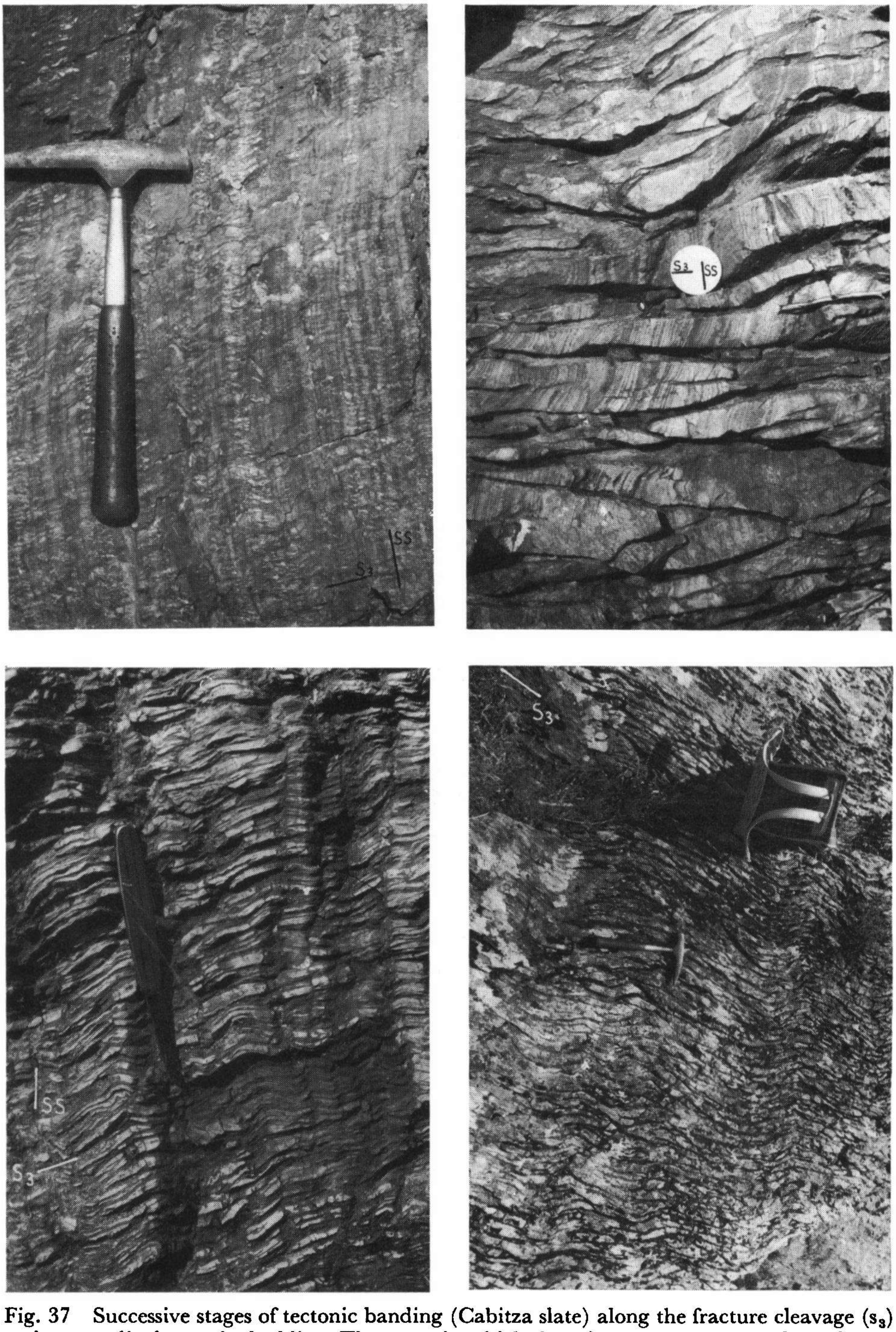


Fig. 37 Successive stages of tectonic banding (Cabitza slate) along the fracture cleavage (s_3) and perpendicular to the bedding. The zones in which the micas are concentrated are deeper eroded than the quartz-rich zones.

a. Locality co-ord. 41,5 — 63,9.
b. Locality co-ord. 37,9 — 73,1.
c. Locality co-ord. 41,5 — 63,9.
d. Locality co-ord. 37,9 — 72,7. Photo taken ⊥ ss.

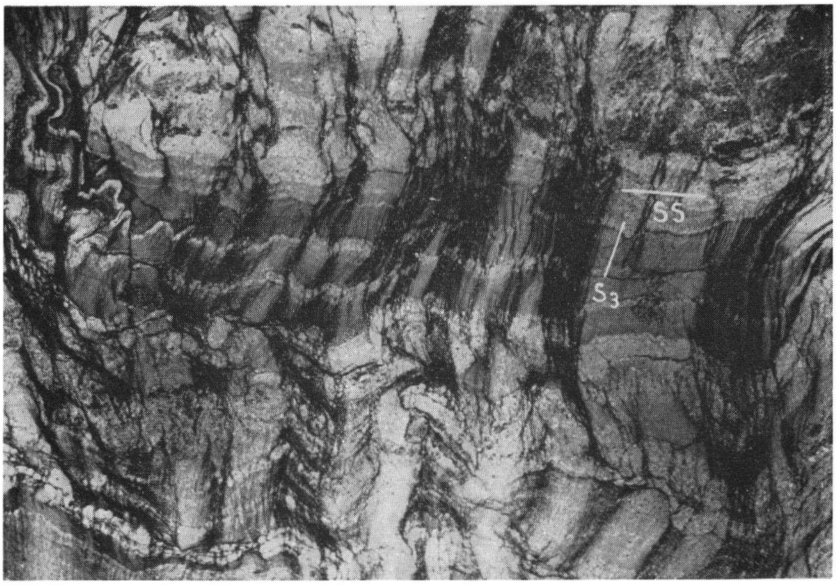


Fig. 38a Thin section of Cabitza slate showing tectonic banding parallel to the s_3 cleavage and perpendicular to the bedding. Locality co-ord. 41,5 — 63,9. (3 ×)

Fig. 38b Detail of fig. a. The dark zone is a concentration of sericite, the lighter zones contain more quartz. (7,5 ×)

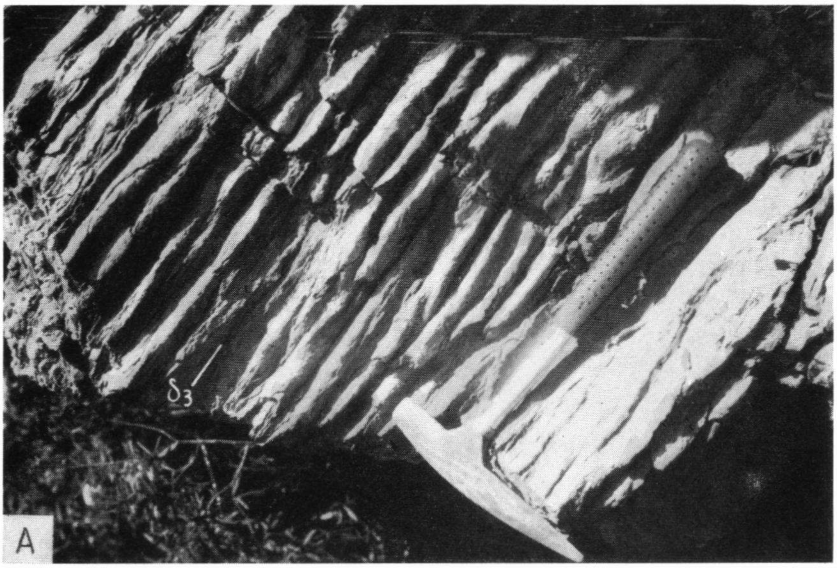


Fig. 39a Bedding plane of Cabitza slate folded by the third phase resembling ripple mark structures. Locality co-ord. 41—65.

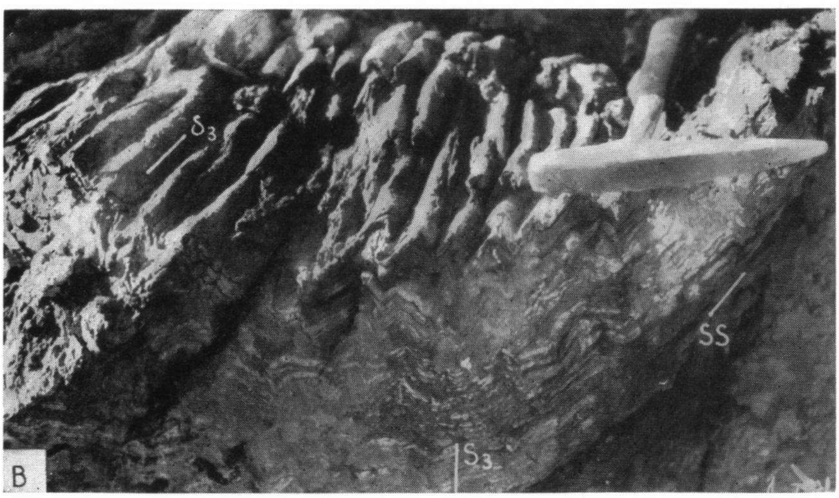


Fig. 39b Cross section of fig. a showing that s_3 is parallel to the axial planes and δ_3 parallel to the fold axes of these folds.

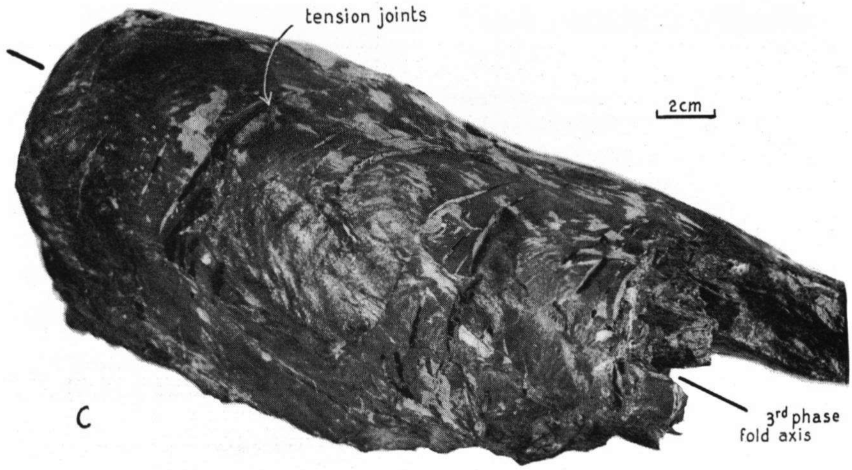


Fig. 39c Detail of the hinge of such a minor fold showing the tension joints that originated parallel to the stress direction.

section, however, it is clear that these "ripples" are folds with s_3 as axial plane (fig. 39b). In these folds a certain elongation took place in the fold axis direction and consequently tension joints ($\perp \delta_3$) developed (fig. 39c). These joints are especially well developed in those outcrops, where these folds are steeply dipping and consequently a parallel with the elongation of the conglomerate pebbles, reduction spots and oölites can be drawn.

FOURTH FOLDING PHASE

The fourth phase is the last Hercynian deformation that folded the rocks of this area. Although this folding is far less important than the preceding ones, its presence has been observed at many places. It seems probable that this phase consists in this part of Sulcis of a conjugate fold system, with one set of folds having vertical NW-SE axial planes and another set with vertical NE-SW axial planes, accompanied by axial plane cleavage. Folds and cleavage belonging to this phase were mainly formed in slate and conglomerate and only sporadically in the more resistant limestone and sandstone Formations. This folding phase mainly caused minor structures and consequently no evidence of it can be found on the geological map. Folds and cleavage of this phase are mainly found east of the N-S co-ordinate 72; west of this line its occurrence is very irregular.

The NW-SE set of the conjugate system has been formed abundantly in the slopes of the Pta di Genna Pira (co-ord. 40,8 — 72,3). The N-S cleavage of the third phase is folded around vertical axes, resulting in rectangular folds with a long N-S and a short E-W limb. In the fold hinges a coarse crenulation cleavage s_{4a}, parallel to the axial plane, has developed well at many places. Poles to the cleavage planes (s_{4a}) and to the axial planes of the NW-SE set are plotted in diagram 3 of fig. 35 and fold axes of this set in diagram 2 (fig. 35).

More to the east in the concession area of the Rosas mines NE of the large dolerite body, a rather regular and coarse crenulation and fracture cleavage (s_{4b})

is developed with a NE-SW strike. This s_{4b} belongs to the NE-SW set of the conjugate fold system. Folds of this set are not abundant, but several of them have been observed. The cleavage (s_{4b}), however, is better developed in this area than s_{4a} at the Pta di Genna Pira, as it is not restricted to fold hinges. Poles to the s_{4b}-planes and axial planes of this set are plotted in diagram 5 of fig. 35, and fold axes and δ_{4b}-lines in diagram 4 of the same figure. Both diagrams show a maximum, indicating that no later deformation folded the rocks of this region. Sometimes the E-W limbs become longer and the N-S limbs shorter, so that the asymmetry is reversed. There is no doubt, however, that the N-S attitude at these places is original and the E-W strike secondary.

In northern Sulcis the sets of the conjugate system are mutually exclusive: where the folds (NW-SE) and cleavage (s_{4a}) are to be found the NE-SW folds and

Fig. 40 Conjugate system of folds and cleavage (s_{4a} and s_{4b}) belonging to the fourth deformation phase. Locality co-ord. 41,5 — 65,9.

s_{4b} cleavage are not and vice versa. There is little or no evidence of a transition zone and so interference between these two systems is rare and difficult to find. However, some examples showing the development of a boxfold (fig. 40) may be seen. It is probable though hard to prove, that both sets are simultaneously developed as shear folds caused by N-S compression. In fig. 41 the shear movement and the compression direction of this conjugate system are sketched.

In the western part of the mapped area (west of Terreseo) folds and cleavage of the fourth phase barely occur. In those outcrops, where cleavage and/or folds of this phase are found outside the "type locality" areas of the two sets (respectively the Genna Pira area for the NW-SE set and part of the Rosas concession for the NE-SW set), the rocks are mostly deformed by the NW-SE set of the fold system.

In other parts of Sulcis and in Iglesiente this phase can be detected too. In most cases, however, one finds cleavages or folds with an E-W trend. These belong to a

Hercynian deformation decidedly post third phase. As both deformations (conjugate set NW-SE — NE-SW and the E-W system) are caused by N-S compression, it seems very probable that all these structures belong to the same deformation phase.

In a part of Iglesiente north of Domusnovas this last deformation phase made cleavage with NE-SW strike and microfolds with axial planes with the same strike direction as the cleavage (Arthaud, 1963). The cleavage in this part of Iglesiente is sometimes developed as a fracture cleavage along which planes a certain movement took place. Arthaud uses the term "Knitterung" to describe this kind of cleavage. Other synonyms used by German authors are "Knickbänder", "Knickzone" and "Flexuren". An English term to describe this phenomenon is knickzones. These knickzones are formed by pairs of coarse cleavage faces (here s_4), which enclose a narrow zone in which the s_3-planes are knicked or flexured. These knickzones occur only in well laminated rocks and are consequently best developed in slates with a regular s_3 cleavage. This lamination is necessary while this special kind of cleavage (knicking cleavage) is only possible by slip along the planes within the knick-zones.

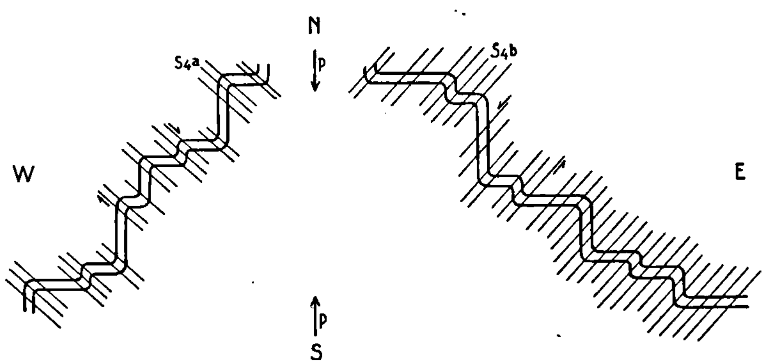


Fig. 41 Conjugate fold system of the fourth phase with shear along the s-planes (s_{4a} and s_{4b}) caused by N-S compression (P).

It seems very probable that the last deformation in the Domusnovas area, with its NE direction and with indications of movement along the cleavage planes, is the same as the NE-SW part of the conjugate system in Sulcis. The cleavage is consequently the same as the s_{4b}.

In Sulcis knick-zones are not very common; a few localities in which they have been found are in the Ordovician slates north of the village of Procaxius (co-ord. 36 — 70,5) and in the Ordovician slates in the north-eastern part of the investigated area (co-ord. 77 — 42,7). In both cases the slates are fractured by s_3 along which slip could easily take place.

ALPINE STRUCTURES

The influence of the Alpine deformation on this part of Sulcis was slight and consisted probably only in a reactivation of pre-existing Hercynian faults and vertical movements. No folding or cleavage was formed during this "orogeny" in this area and it seems that in whole Sardinia this kind of deformation did not take place during this time.

The Alpine deformation consists mainly of large scale blockfaulting, with important vertical movement along these faults. According to Teichmüller (1931) movements started already during the Cretaceous (Laramide phase) and lasted throughout the Tertiary. Large structures like the Campidano rift-valley, the Nurra depression, the Tirso and Cixerri valleys and the depression in south-west Sulcis were formed by this Alpine deformation. It is obvious that most of these large morphological units follow Palaeozoic directions caused by the Sardic and Hercynian deformation phases (Vardabasso, 1956).

The large NW-SE trending Campidano rift-valley is one of the most conspicuous Alpine structures of Sardinia. This rift-valley runs from coast to coast for about 100 km and is about 15 to 20 km wide. The greatest subsidence of this rift took place during late Tertiary times. Quaternary deposits sometimes reach a thickness of over 100 m. This indicates a rather important subsidence in sub-recent times. As there is still an important supply of material and as in the last century there was a salt-

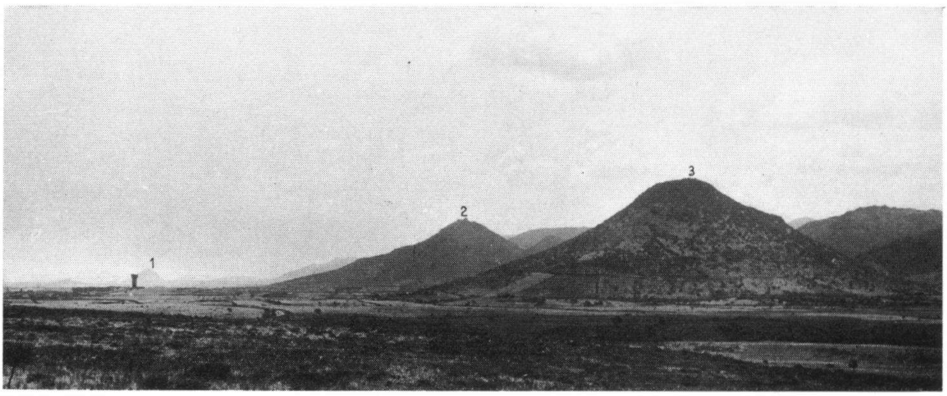


Fig. 42 Cixerri valley with volcanoes on the border faults. Photostation between Iglesias and Domusnovas, looking ESE. 1. Casto di Acquafredda 2, M. Goioisa Guardia 3. M. Exi

water lake with a marine fauna in the middle of the rift-valley, one assumes that the subsidence is still going on. Some boreholes made in the north-western part of the Campiano prove a thickness of upper Tertiary rocks of over 2000 m. Along the normal faults, along which the rift subsided, volcanic activity most probably took place during the Oligocene. Near the village of Bacu Abis, some km west of the mapped area, volcanic ashes are covered by Miocene deposits (Feruglio, 1924).

The mapped area is bordered in the north by the Cixerri valley. This valley forms a branch of the Campidano rift and is bordered by normal faults. The downthrow of this valley is not large since outcrops of Palaeozoic rocks occur (e.g. Mte Ollastus, west of Villamassargia). The faults, however, reach a great depth, as proved by the occurrence of several volcanoes along these faults, but only at the south of the Cixerri valley. Some fine examples of these volcanoes are M. Exi and M. Gioiosa Guardia near the village of Villamassargia and the peak on which the ruins are situated of the castle of Acquafredda south of Siliqua (see map and fig. 42). These border faults are probably fault zones consisting of several parallel faults. In the south the mapped area is just as in the north bordered by E-W faults of Alpine age. Along these faults the basin subsided and was filled up for the greatest part with volcanic rocks and sediments of the Tertiary.

It seems that the Palaeozoic rocks between the two large E-W faults zones in the north and in the south of the mapped area were barely affected by the Alpine deformation. It is possible that the fault system in the north-eastern part of the mapped area (M. Orri region, co-ord. 42—79) is of Alpine age, but this is hard to prove. According to Minucci (1935) the repetition of many small conglomerate bands in the M. Orri region is caused by Alpine faults. This, however, is not true. Along these faults small valleys came into existence and as these valleys are covered with scree and bush no outcrops of such a fault is found. If one compares both sides of such a valley it is seen, that these faults have no important throw. The repetition conglomerate-slate is consequently a stratigraphic one and not a tectonic one. It is difficult to map these faults in the field, but they are obvious on the aerial photographs as they clearly affect the morphology.

DISCUSSION

If one compares the official geological map of the R. Uff. Geologico d'Italia (1938, scale 1 : 100000) with the geological map presented here (scale 1 : 25000), one sees that there are almost no differences in interpretation between the western parts of the maps. On the eastern parts, however, large differences occur. This is due to the difficulty of distinguishing Ordovician from Cambrian slates, especially where conglomerate fails. With a certain experience, however, it is possible to make this distinction. The Cabitza slates are mostly well laminated ("scisti listati") and

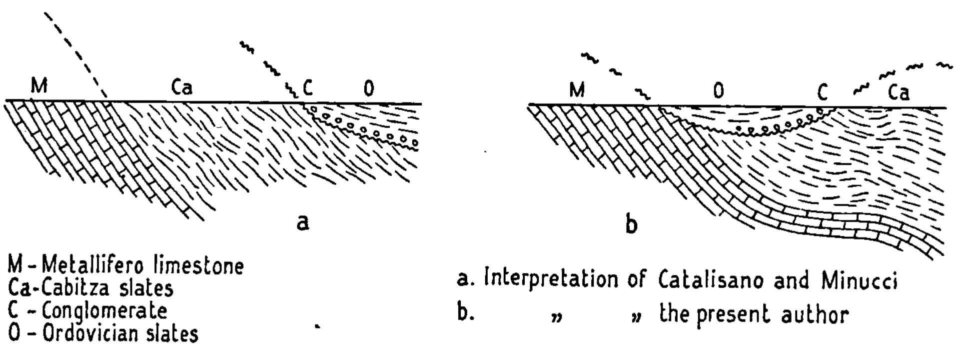


Fig. 43 Different interpretations responsibie for the differences between the geological map of the R. Uff. Geol. d'Ital. (1938) and the map of the present author.

intensively microfolded, while the Ordovician slates are poorly layered and less intensively deformed. It is possible to trace this contact in the field and now and then one finds small conglomerates at the transition zone, which clearly indicates that the mapping method is correct. It is easily understood why this interpretation error is made by Catalisano and Minucci, who mapped this part of Sulcis. If one passes the following sequence: Metallifero limestone-slate-conglomerate and slate again, it seems correct to call the first slate Cabitza and the last Ordovician. In this case, however, the Ordovician lies unconformably on Metallifero limestone (without conglomerate) and on Cabitza slate (with conglomerate); see fig. 43.

Another important difference is the way of mapping the Silurian rocks. Near C. Sias (co-ord. 46 — 77,2) one finds the black slate and the *Orthoceras* limestone,

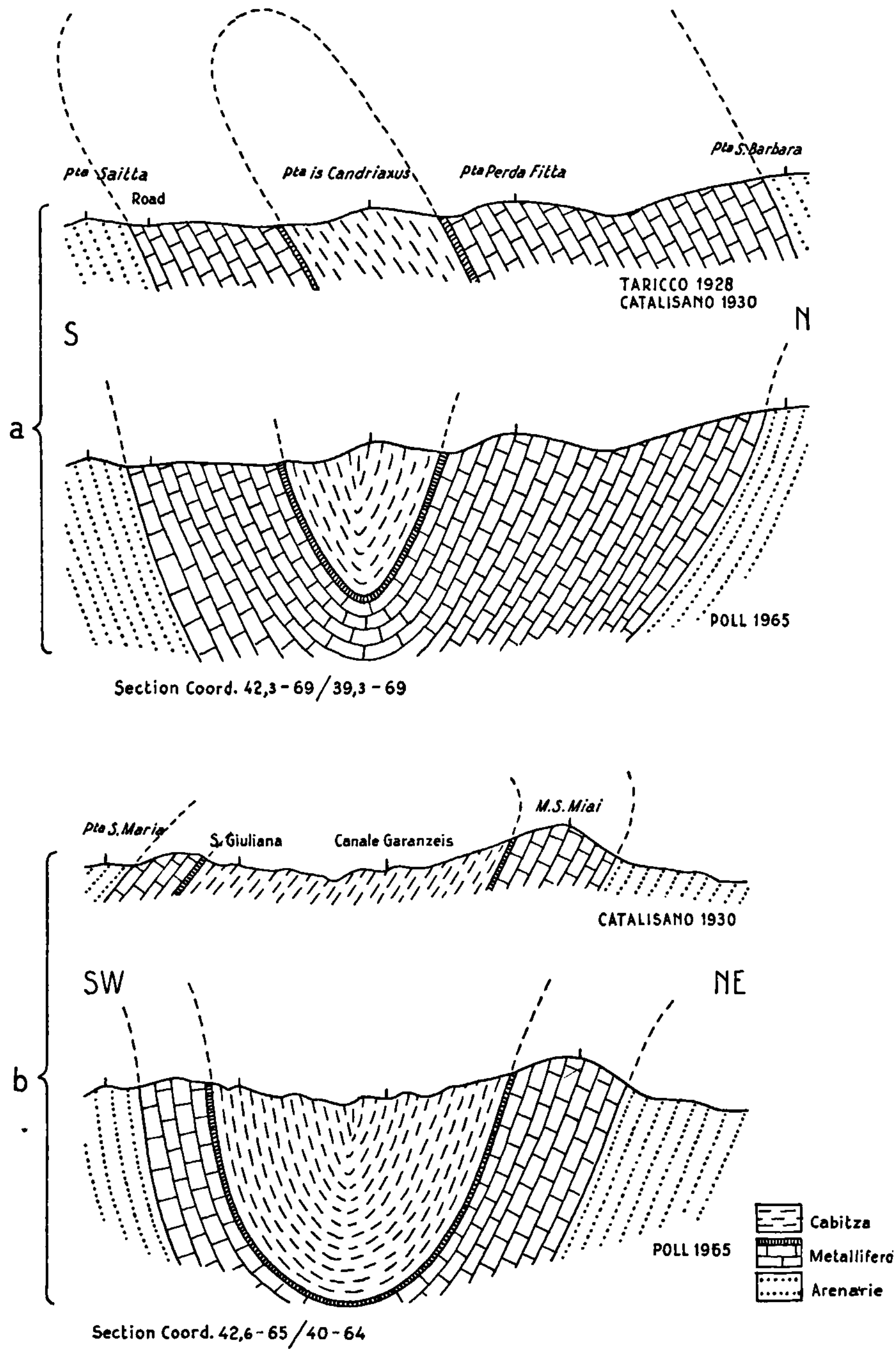
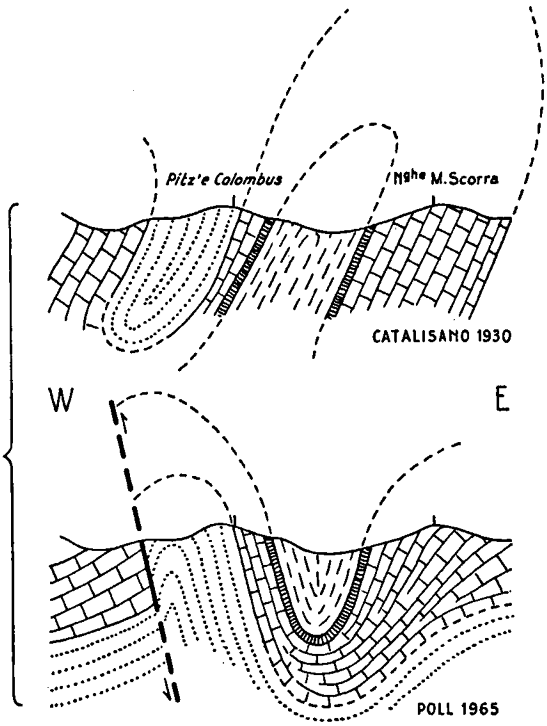


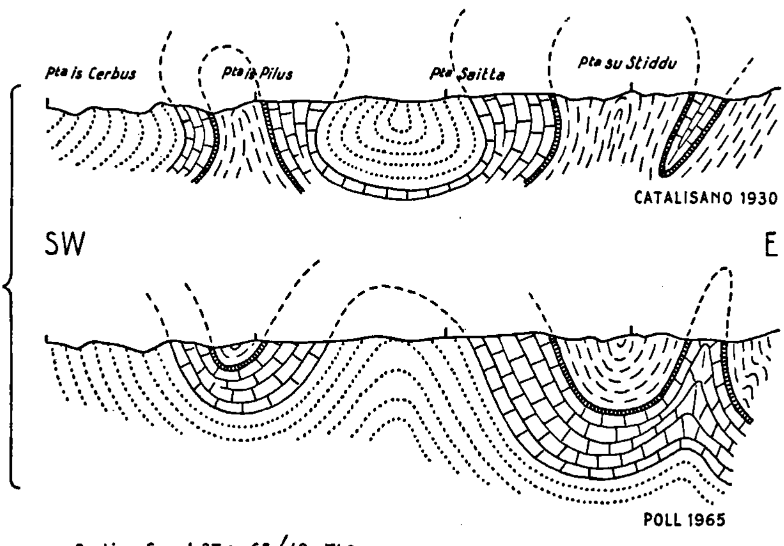
Fig. 44a, b, c and d. Profiles by Taricco (1928) and Catalisano (1930) according to the former conception of the Cambrian stratigraphy in comparison with the profiles of the present author.

c



Section Coord. 42,3 - 71,4 / 42,3 - 72,9

d



Section Coord. 37,6 - 65 / 40 - 71,3

obviously belonging to the Silurian. North of C. Sais post-Silurian rocks are indicated on the old map, but there is no unconformity or a sharp transition; therefore no separation is made on the present map. According to the old map a narrow zone of Silurian rocks runs through the mountains and crosses the street Siliqua-Acquacadda (locality co-ord. 42,2 — 83,2). In the field there is absolutely no difference between the rocks north and south of this "zone" and consequently the rocks in the north

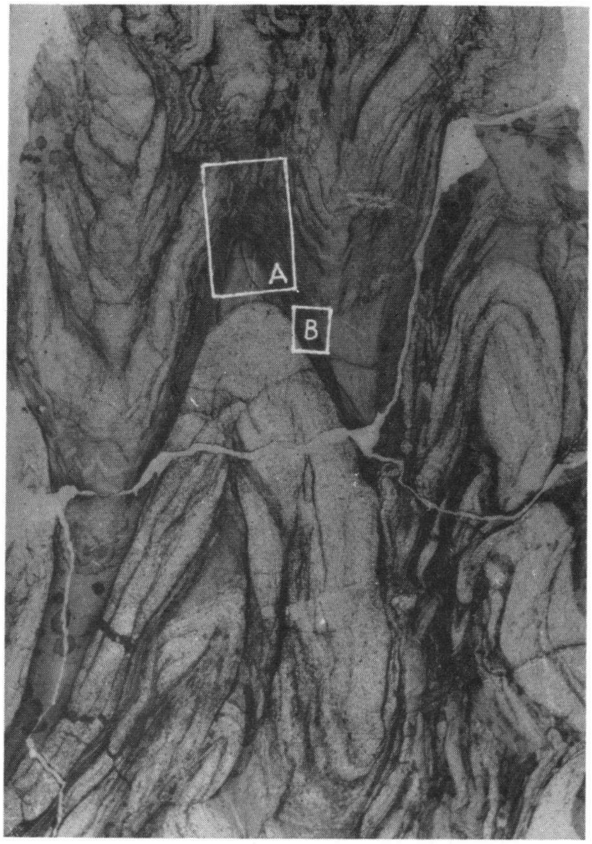


Fig. 45 Thin section of Cabitza slate. Almost the complete tectonic history can be traced back in this sample. In fig. d. three successive stages of deformation are sketched. The third deformation of fig. d. corresponds with the third folding phase (N-S, s_3). Consequently it seems very probable that the first deformation of this rock corresponds with the Sardic folding (s_1) and the second deformation with the second folding phase (s_2). a. thin section of Cabitza slate. Locality co-ord. 38,7 — 78,1; (2×). b. detail of fig. a; (11×). c. detail of fig. a: (27×). d. successive stages of deformation of this rock.

are incorporated into the Ordovician on the map of the present author. The Ordovician-Silurian transition most probably lies north of the mountain range in the Cixerri valley and is covered by Tertiary and Quaternary deposits.

After Catalisano's mapping (1930) the subdivision of the Cambrian in three formations was proved to be reverse. Consequently all profiles have to be revised (fig. 44).

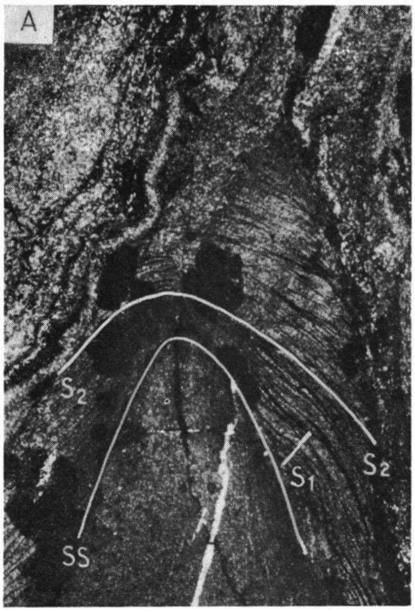


Fig. 45b

Fig. 45c

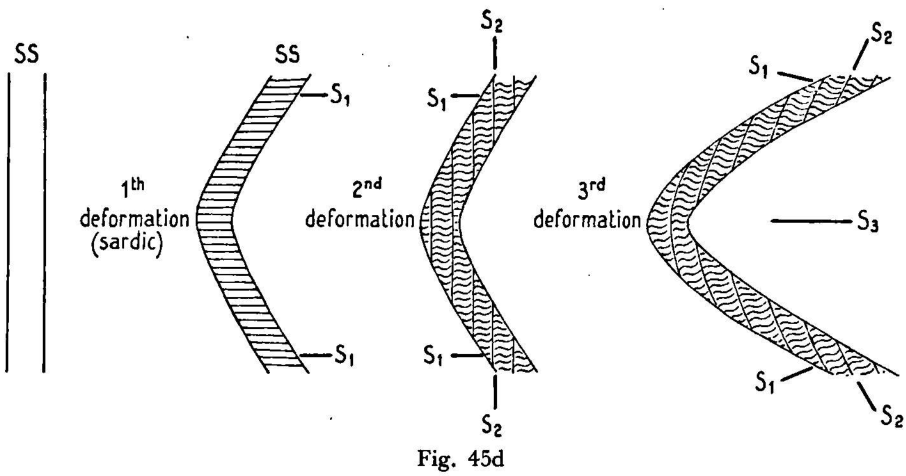


Fig. 45d

It is impossible to date the Hercynian folding phases in Sulcis. The youngest Palaeozoic rocks of Silurian age are gently folded by an E-W phase (presumably the second phase) and consequently the second, third and fourth folding phases are post-Silurian. In Iglesiente this dating can be done better as younger rocks occur, but it remains difficult. A correlation of these folding phases with the general division of Hercynian phases (Bretonic, Sudetic, etc.) is impossible. It seems that in Iglesiente and especially in the Fluminimaggiore area unconformities exist between the black slates and *Orthoceras* limestones of Silurian age and the "post-Gothlandian", deposits of Devonian-Carboniferous age, and between the "post-Gothlandian" deposits and the Permo-Triassic. This last unconformity is obviously Hercynian but the first is definitely older. If the first unconformity is clearly an angular one due to a folding phase, it is obvious that this phase, at least qua age, is Caledonian. Unfortunately the present author never visited these localities and consequently cannot give interpretation of these phenomena. According to Zuffardi (pers. comm.) the structural scheme of the Arburese area (N-Iglesiente) is: "gentle major folds with fold axes ENE or NE and gentle minor folds with fold axes perpendicular to the first set. In this area no fold system with N-S axes occurs". It seems probable that the deformation system of Arburese corresponds with the fourth phase (conjugate system) of N-Sulcis. Hence the fourth deformation phase must be Hercynian. From the absence of N-S structures in the Arburese area one can conclude:

a. that the N-S folding phase is older than the "post-Gothlandian" rocks, hence Caledonian, or
b. that the N-S folding phase was never present in this particular area and consequently no age determination of this phase can be done here, or
c. one of the two fold systems of the Arburese area is caused by the third (NS) folding phase, since third phase structures are not everywhere exactly N-S.

In the Gerrei area (about 60 km east of Iglesiente) the Devonian limestone is E-W folded and N-S refolded. Both phases are obviously Hercynian and it is tempting to compare the structures of this area with those of the Iglesiente and Sulcis areas.

We have seen on one of the preceding pages, that the N-S zone approximately along the co-ordinate 71 is an important structural fold and fault line probably already determined by a thinner Metallifero sequence as is seen in the north (co-ord. 42,5 — 71,5). The N-S line is furthermore important as it forms an interesting division between the geology of the western part and the geology of the eastern part of the investigated area. In the western part the Sardic direction is E-W and the Hercynian main folding N-S. No Ordovician rocks occur in this area except near Villamassargia (co-ord. 47,5 — 68,5). In the eastern part it seems that the Sardic direction turns to NW-SE and the direction of the Hercynian main folding to NE-SW. Large parts of this eastern area are covered with Ordovician rocks. The origin of these differences and its possible relations with the important N-S zone is not yet clear.

IGNEOUS ROCKS, METAMORPHIC ROCKS AND ORES

INTRODUCTION

Della Marmora (1857) has distinguished three Palaeozoic magmatic phases in Sardinia: granite, quartz-porphyry and diorite. Cavinato (1937, 1939 and 1948) added porphyrite to this sequence and came to the following division: infra-tectonic porphyrite, post-tectonic granite, porphyry and diabase (= diorite of della Marmora).

The area investigated by the present author contains a variety of Hercynian igneous rocks as dolerite (diabase of Cavinato), granodiorite bordered with volcanic rocks (M. 's Orcu) and small volcanic and hypabyssal dykes. In the north and in the south of the mapped area, volcanism took place along normal faults during the Tertiary. The rocks formed in this way are mainly of the andesitic type.

The dolerite intrusion caused small contact metamorphic zones, especially in the limestones. After the dolerite intrusion, hydrothermal and pneumatolytical action took place. This last action altered the dolerite partly into a meta-dolerite and produced skarn zones in the limestone. The limesilicate rocks are called "roccia verde" (i.e. greenstone) by the mining people, which brought confusion as the same name was applied to the dolerites.

The rocks underwent only slightly regional metamorphism. Sericite, chlorite and quartz are the only newly formed minerals and the limestone is cryptocrystalline ("calcare ceroide"). These rocks can be classified in the lower epi-metamorphic zone. Rocks of higher regional metamorphism can be found about 30 km southeast of this area and at several places in the middle and north of Sardinia.

Together with Iglesiente, this area forms the most important mining district of Sardinia. Among these chiefly sulfidic ores, galena (PbS) and sphalerite (ZnS) occur most frequently. Almost all mines in northern Sulcis belong to the Rosas group of the A.M.M.I. and are situated in the eastern part of the investigated area. A detailed map of this area is appended to this paper.

The author will give only brief descriptions of the different types of rocks and ores, without going into pure petrological, mineralogical and genetical problems.

IGNEOUS ROCKS

Hercynian igneous rocks

Dolerite. — From both Iglesiente and Sulcis these basic rocks are known and described. The best and the largest example is the long-stretched body of dioritic composition in the concession area of the Rosas mines, seen on the eastern part of the map (1 : 25000) and especially on the more detailed map (1 : 10000). The other dolerite bodies are small and in most cases extremely weathered. Sometimes metasomatically altered limestone is wrongly described as "diabase". In the literature on these regions the name "diabase" is used, but according to Harker (1960-a), the more exact name is dolerite, which is partly synonymous. Sometimes the rock is called a "diorite", which is right regarding the composition, but the texture is obviously ophitic, which indicates that this rock is hypabyssal and not plutonic.

Della Marmora (1857) was the first geologist to mention this rock. Riva (1898) gave a very good description of the "diabasic formation of Rosas". Later on many authors described this rocktype (Taricco 1928; Catalisano 1930; Borghesan 1935, 1936, 1942; Cavinato 1937 and Cadisch 1938), but Riva's description is the most comprehensive.

The colour of this rock is dark green, which is mainly due to the chlorite and to the hornblende. The texture is fine grained and the rock shows no foliation. In a thin section it is seen that the columnar crystals of feldspar have no preferred orientation and are surrounded by large xenomorphic augite plates. This phenomenon is known as the ophitic texture and is due to simultaneous crystallization of the two minerals (Harker 1960-a).

The composition of the dolerite changes accordingly as it is more or less transformed by later metamorphism, but the general composition is:

primary minerals (more or less in advanced stage of decomposition)
- plagioclase-andesine, with albite type twinning
- pyroxene -augite (titane-augite?), light rosa

secondary minerals (formed by decomposition of the primary minerals)
- amfibole-hornblende, blue-green
- epidote -epidote, klinozoisite and zoisite in small fracture zones
- chlorite -mainly responsible for the green colour of the rock
- calcite
- muscovite

accessory minerals
- apatite
- titanite
- leucoxene

Cavinato (1937) made a chemical analysis of the dolerite with the following result:

SiO_2 —45,78%	Fe_2O_3— 6,72%	MgO —4,05%	Pb_2O_5—0,03%	
TiO_2 — 1,33%	FeO — 3,75%	K_2O —0,93%	CO_2 —0,21%	100,25%
Al_2O_3—21,00%	CaO —10,70%	Na_2O—2,83%	H_2O —2,92%	

From this analysis compared with analyses from other basic igneous rocks Cavinato concluded that the dolerite dyke from Rosas is the most basic rock on Sardinia. In some of the Rosas mines special attention is paid to the exact position of the dolerite body as the contact dolerite limestone is in some cases mineralized. Later on by the discussion of the ores we will see that the relation dolerite — ore is not a genetic one.

Beside the large dyke several small dolerite outcrops can be found in the Rosas area. Borghesan (1935) described a "gabbro diorite" body of 60 m length and 25 m width, found in Pozzo Camerana (see map 1 : 10000) and a body at 75 m depth in the Marchesa mine. At the surface almost no trace of these bodies can be found. Taricco (1928) mentioned several places where he observed "diabase" (co-ord. 42,3 — 65,2; 38,2 — 67,6; 36,7 — 67,4; 38,1 — 70,6; 36,3 — 72,6), but most of these outcrops could not be traced back.

The dolerite is a derivative from a magma of gabbro-dioritic composition and is most probably of Upper Carboniferous — Lower Permian age.

Biotite-granodiorite. — Granite occupies large parts of Sardinia, especially in the northeastern part of the island, but also in Iglesiente and Sulcis. In eastern Sulcis the granite is partly covered by Palaeozoic rocks, but is seems very probable that it concerns one and the same large granite batholith. Many contacts of granite with sedimentary rocks are fault contacts. At some places the contact metamorphic zone is narrow and the degree of metamorphism low. Sometimes such a zone even fails. Sediments of the Upper Devonian and Lower Carboniferous are the youngest deposits that underwent a thermal influence of the granite. Therefore a Middle Carboniferous age of the granite is assumed. In Sulcis no dating can be made as only older Palaeozoic rocks occur. The "granite" of M. 's Orcu was so far supposed to belong to the large batholith mentioned above.

In the mapped region "granite" occupies only a small area, but forms by its peculiar position in the folded host rock a remarkable phenomenon. The "granite" stock of M. 's Orcu (see map) is obviously an intrusive one. There is a small zone of contact metamorphism in the surrounding host rock (silicification of the limestone and dolomite). The curvature of the major NNW-SSE fold, made by the third deformation phase, formed apparently a weak zone past which the "granite" intruded. The composition of this rock is:

quartz	— completely non undulose (crystallization is post tectonic)
plagioclase	— mainly albite lamellation combined with Carlsbad and pericline twinning. Strongse ricitization, especially of the cores. The cores are idiomorphic, the rims xenomorphic. The An-percentage varies from 0% (albite) to 53% (labradorite). The cores have a higher An-percentage than the rims.
K-feldspar	— small crystals, sometimes sericitized
biotite	— uniaxial
chlorite	— secondary after biotite
epidote	— clinozoisite near chlorite and biotite
zircon	— rounded and idiomorph
calcite	— secondary in plagioclase
sericite	— in feldspar
apatite	— long prisms
ore minerals	

The texture is fine grained and the name of this rock is biotite-granodiorite.

Volcanic rocks bordering M. 's Orcu. — The western and northern part of the granodiorite stock is bordered by a rock type with a completely different texture and composition. Catalisano (1930) described this rock as porphyritic. On the older geological map (1938) of this area this rock is indicated as a porphyry. The contact between the granodiorite and this "porphyry" is either not exposed or not accessible, but at some places, according to Catalisano, dykes of this rock type cut into the granodiorite. From this phenomenon and from the completely different texture of the two rocks he concluded that it concerns two different intrusions; the granodiorite first and the "porphyry" later.

This rock, however, is obviously volcanic and can be divided into two different types: tuffs and flows.

The tuff has a fine grained groundmass and contains xenomorphic crystals of quartz and plagioclase and in lesser quantity biotite, chlorite and calcite. Most obvious are the fragments of sedimentary rocks (up to 10 cm ⌀) as limestone, slate and sandstone (fig. 46) of which the limestone fragments are dominant. Such a composition and texture is rather "unusual" for a porphyry as is indicated on the older geological map.

The flows are light coloured well laminated rocks with flow structures (fig. 47). The ground mass of this rock type is mainly glassy with small bands of quartz crystals and sometimes small rock fragments. The components clearly indicate that these flows are acid ones.

Both rock types occur together and are deposited in a sequence tuff-flow-tuff etc. This layering is almost horizontal or gently dipping and these rocks lie unconformably on the limestone and dolomite of the Metallifero Formation. The unconformity is not exposed but obvious if one compares the orientation of the surrounding limestone and dolomite with the orientation of the volcanic rocks.

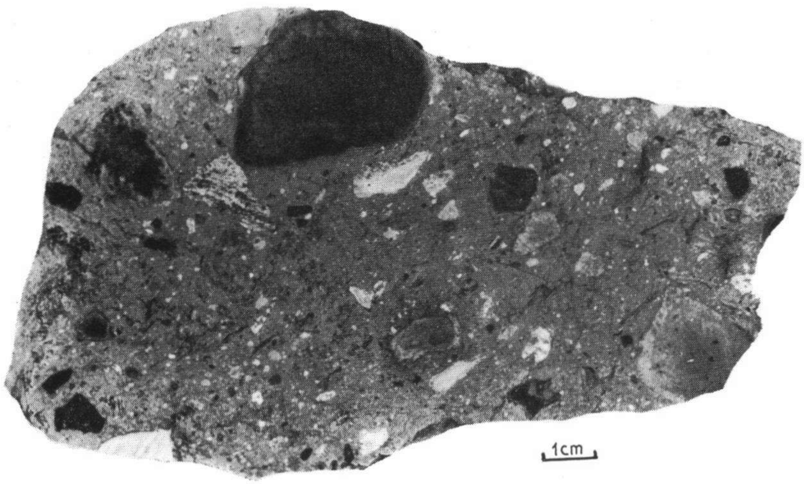


Fig. 46 Tuffitic rock west of M. s'Orcu with limestone and sandstone fragments. Locality co-ord. 37,5 — 66,8.

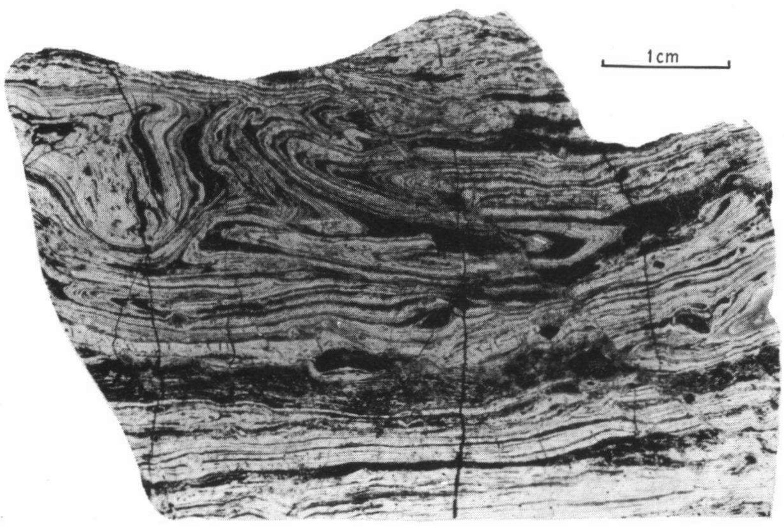


Fig. 47. Light coloured, well laminated, volcanic rock with flow structures. Locality co-ord. 37,5 — 66,8.

Thus we have a core of plutonic rock (biotite-granodiorite) partly surrounded by volcanic rocks and not by a hypabyssal rocktype as Catalisano thought. Tuffs are formed by accumulation of volcanic matter together with material derived from erosion, if the tuff is formed in an environment of sedimentation. Normally tuffs are formed immediately around the volcanoes. Apart from the tuffs and flows no proof of volcanic activity can be found in the direct neighbourhood, unless we consider the granodiorite stock as a volcanic pipe. In that case the typical position of the tuff in respect to the granodiorite is easily explained. The chemical composition of granodiorite (plutonic) and rhyodacite (volcanic) is the same. The textural differences originated through different crystallization conditions. If volcanic magma sticks in the pipe the cooling will be slow and the crystallization uniform. The texture of the so formed rock will be plutonic. Thus it seems very probable that the M. 's Orcu is virtually a volcanic pipe. The original cone and almost all tuffs are taken away by erosion. In this conception we cannot stick any more to the dating of the large granites in the other regions to establish the age of this granodiorite. The only thing one can observe is that the granodiorite is post-tectonic (intruded after the forming of the structures, and containing non-undulose quartz). As no younger rocks occur, this is the only statement one can make about the age. Consequently it is a possibility that this "volcano" belongs to the Tertiary volcanism.

The tuffs and flows are deposited on an erosion surface after the folding of the area. This indicates an important hiatus, due to erosion, between the Middle Cambrian limestone and dolomite, and the volcanic deposits. The present erosion level must be approximately the same as during the deposition of the tuffs. If this volcano is Hercynian, this coincidence is accidental; if this volcano is of sub-recent times, there is no coincidence to explain. An age determination of the granodiorite will yield the solution of this problem.

Dykes. — Besides the igneous rocks mentioned above, a few dykes occur in Sulcis. These dykes have in general a width of some metres and a length up to about 100 m. The position of these dykes is given in grid co-ordinates (see map).

1. 39,3—66,9 Small andesitic dyke (1,5 m wide), intruded in the "calcescisti" along the road, west of the water source of Terreseo.
2. 42,3—68,6 Small dyke (1,5 m wide and 100 m long) parallel to the s_3 fracture cleavage. This rock is an andesite according to Harker (1960-a), or a basalt according to P. Niggli (1939).
3. 41,8—69,4 N-S trending dyke near the Giuenni mine. This rock is difficult to determine but it concerns most probably an andesitic rock.
4. 42,2—71,2 The rock is decomposed, but the texture is preserved, and it seems that this rock is volcanic. It contains several well rounded fragments of sedimentary rock and therefore this rock can be described as a "tuffitic" andesite.
5. 39,2—72,2 Small dyke (2 m wide) intruded in the s_3 cleavage direction. This dyke is more complex as it is composed of two intrusions. In a thin section it is seen that the second intrusion is finer grained and contains fragments of the first along the contact. Both rocks are basalts of equal composition.
6. 40,5—65,3 No contact between this rock and the surrounding Cabitza slates can be found. Large and well rounded boulders of this rock, preserved by erosion, are lying on the slates. The texture is typically hypabyssal. The composition is lamprophyric, but too much quartz occurs and it is consequently a micro-tonalite.

7. Quartz dykes

Many quartz dykes occur in this part of Sulcis, mainly east of the N-S co-ordinate 71. These dykes are decidedly larger and more frequent than the previous ones. It is sometimes difficult to distinguish quartz dykes from the tectonic quartz breccia. The outcrops of quartz breccia are irregular in contrast to the straight and regular dykes. The quartz dykes are formed along fracture zones.

It is striking that almost all these dykes (1—5) consist of volcanic rocks. Only number 6 is hypabyssal. As most of these dykes are intruded along cleavage planes of the third folding phase (s_3), we may conclude that these intrusions are late- or post-Hercynian.

We have seen that the main volcanism of this area took place during the Alpine orogeny. It is therefore tempting to connect the small volcanic dykes with this volcanism. In the authors opinion, however, these dykes are connected with a Hercynian volcanic phase. This phase probably also gave rise to the granite stock and its surrounding tuffs and flows of M. 's Orcu. The real hypabyssal dykes and the quartz dykes are most probably related to the Hercynian granite intrusions of Carboniferous age.

Alpine igneous rocks

Volcanic rocks. — On Sardinia volcanic activity took place during the Hercynian- and Alpine orogeny. Since the Alpine volcanic phases are more important than the Hercynian, large parts of Sardinia are covered with volcanic rocks of varying composition of Tertiary and Quaternary age.

Della Marmora again was the first who studied these rocks and made a division of different phases of extrusion. Later on these rocks became the subject of extensive study by several authors (Bertolio, 1895; Washington, 1914; Burford, 1933; Cavinato, 1939 et al.).

The Tertiary volcanism probably took place during the Oligocene and rhyolites, rhyodacites, dacites, trachites, trachy-andesites, andesites, basalts and phonolites were formed. The most recent volcanic activity took place during the Quaternary and gave rise to basalts. This activity is not yet completely finished as several hot springs in different parts of the island testify.

In this part of Sulcis volcanic rocks occur along the northern border of the mountain range, but mainly south of the area of Palaeozoic rocks. Most of the volcanic rocks in the north are obviously bound to the E-W normal faults along which the Cixerri valley subsided. This phenomenon is already mentioned by Bertolio (1895) who made a study of these particular rocks around the village of Siliqua. The main occurrences of volcanic rocks are the three distinct cone shaped volcanoes (M. Exi, M. Gioiosa Guardia and M. Castillo di Acquafredda; fig. 42).

M. Castillo di Acquafredda:

Bertolio's description (1895) of this hornblende-trachyandesite is perceptive: "the texture is porphyritic with large phenocrysts of feldspar and a ground-mass with a distinct microlite development and a complete lacking of flow structures". According to Bertolio this rock crystallized beneath the surface and consequently the texture resembles the texture of hypabyssal rocks. Thus the shape of the volcano nowadays is not the form of the original cone, but originated by strong erosion of the surrounding rocks in comparison to the more resistant pipe. The composition of this rock is:

plagioclase — oligoclase, andesine and labradorite. Strongly zoned (sometimes oscillated) and twinned on different laws.
amphibole — hornblende, brown and green
K-feldspar — orthoclase and anorthoclase
accessory and secondary minerals — zircone, apatite, biotite, chlorite and ore minerals. Feldspar occurs in three generations. Two generations appear as phenocrysts and the third is seen as microlite in the ground-mass.

Volcanic rocks near Villamassargia:

South of Villamassargia many outcrops of andesite are found. Two of these occurrences, M. Gioiosa Guardia and M. Exi, are distinct volcanoes. The other outcrops are irregular formed. The volcanic rocks here are popularly called "péperi",

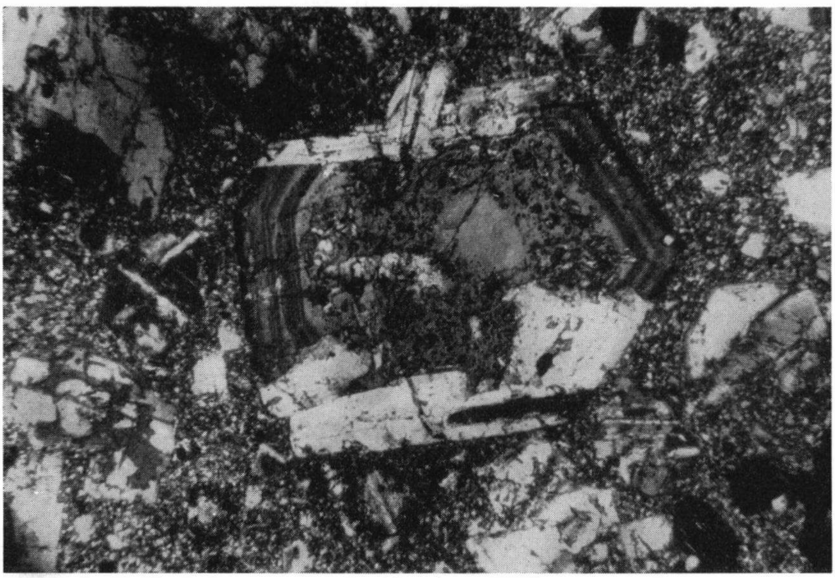


Fig. 48 Andesite with feldspar showing twinning and oscillating zoning. Locality co-ord. 45,8—72. (32 ×)

which means pepper, indicating the dark patches (hornblende) on a pale green priming colour (ground-mass). The composition of this rock in different outcrops is almost equal, but texture, colour and minor constituents differ from place to place. The An-percentage of the plagioclase differs much between the various occurrences. The An-percentage of the plagioclase of the southern part of the M. Gioiosa Guardia varies from 35 % (andesine) to 57 % (labradorite), while the An-percentage of the plagioclase of the M. Exi varies from 86 % (bytownite) to 94 % (anorthite). The plagioclase shows beautiful twinning on different laws and oscillating zoning (fig. 48). Hornblende is found in all thin sections as large, green, idiomorphic crystals, sometimes zoned and twinned. In advanced stage of decomposition the hornblende is replaced by chlorite and calcite without losing the original crystal boundaries. In the ground-mass one finds the following constituents: plagioclase, K-feldspar, hornblende, biotite, chlorite, apatite, zircone and sometimes some pyroxene. This rock was called a porphyrite by Bertolio (1895), but the volcanic character of these occurrences is evident. Therefore a better name of this rock is hornblende-andesite (Harker, 1960-a). Sometimes, however, when the An-percentage of the plagioclase is high (bytownite) the name can also be hornblende-basalt (P. Niggli, 1939).

METAMORPHIC ROCKS

Introduction

In Sulcis the Palaeozoic rocks underwent different kinds of metamorphism, as regional metamorphism and contact or thermal metamorphism.

Regional metamorphism: The whole sequence of Lower Palaeozoic rocks in Sulcis is in a very low stage of regional metamorphism. The original shales changed into slates and the limestone became cryptocrystalline. Interesting mineral parageneses did not originate and therefore this type of metamorphism will not be discussed.

Contact metamorphism: Contact metamorphic rocks form the most interesting rock types in this area. These rocks can be divided into lime-silicate rocks ("hornfelses" according to Cavinato, 1937) and spotted slates.

Lime-silicate rocks

Part of the limestones of the Metallifero Formation and some small limestones of the Ordovician are converted into green coloured lime-silicate rocks. These lime-silicates are partly due to the dolerite intrusion, but mainly caused by hydrothermal and pneumatolytical action after the dolerite intrusion. The mineral assemblage is typically a "skarn" mineral paragenesis. In the mines this rock is called "roccia verde".

Borghesan (1936) described lime-silicates from the Rosas area and their relationship with the ores. Cavinato (1937) called these lime-silicate rocks "hornfelses" and his description of these rocks is the most comprehensive one. He made the following division:

1. quartz-epidote-etc.
2. quartz-diopside-epidote-etc.
3. epidote-diopside-amphibole-etc.
4. amphibole-garnet-etc.
5. quartz-epidote-garnet-etc.
6. amphibole-chlorite-calcite-etc.
7. garnet-quartz-amphibole-etc.
8. garnet

The distribution of the different types of lime-silicate rocks is extremely irregular. They occur mainly as narrow zones along fractures along which the hydrothermal and pneumatolytical action took place. It is not possible to make this division in the field while these types merge into each other rapidly.

The dolerites of Rosas were subjected to this contact metamorphism, which indicates that this metamorphism is post dolerite intrusion. Small ore-bearing veins found in the dolerite and also, but less frequently, in the Ordovician slates are formed simultaneously with the skarn formation.

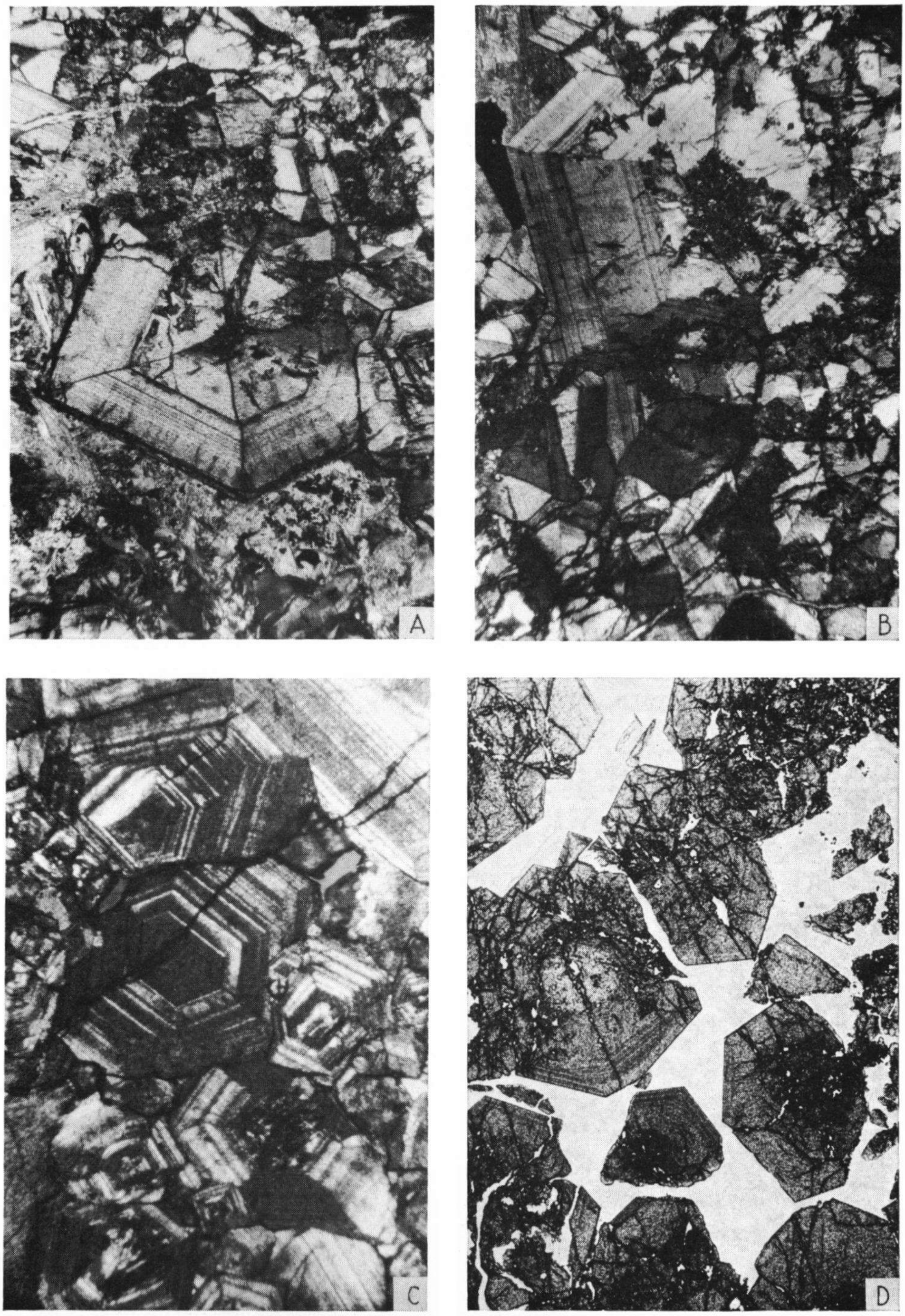


Fig. 49 Idiomorphic, zoned and anomalous birefringent andradite in lime-silicate rocks of the Rosas area. a, b and c with x-nicols, d with //-nicols. (25 ×)

The most conspicuous mineral in the lime-silicate rocks is garnet, which closely resembles vesuvianite. These garnets are beautiful, idiomorphic, zoned and anomalous birefringent crystals, found in almost every outcrop of lime-silicate rock (fig. 49). The general composition of the garnets determined from $\bar{a}_0$ and n_d according to the method proposed by Frietsch (1957), varies from 70 % andradite and 30 % grossular to 80 % andradite and 20 % grossular. Garnetite, almost completely consisting of garnet with some quartz and calcite, is found near Piazzale Martha (co-ord. 41,2 — 77,3) in a band of about 10 m wide and over 100 m long. These garnets are idiomorphic, honey coloured crystals of about 3 mm ⌀.

Cavinato (1937) ascribes the peculiar optical property of the garnets to long lasting and changing metamorphism; first pneumatolytical conditions were present during which the garnets were formed, followed by hydrothermal action during which the garnets became zoned and birefringent. Rosetti (1946) extensively studied the garnets from Oridda (E-Iglesiente), which closely resemble the garnets from Sulcis. According to Rosetti the optical anomaly of these compound crystals (mainly andradite) is due to pseudomorphic ("paramorphic") phenomena with chemical transformation of garnet into vesuvianite, caused by later hydrothermal action.

The other minerals from the lime-silicate rocks are:

epidote group	— epidote, clinozoisite, zoisite and pistacite
pyroxene group	— diopside-hedenbergite
amphibole group	— tremolite-actinolite
wollastonite	— especially at sa Marchesa mine, co-ord. 37,6 — 71,8.
quartz calcite	} almost always present

These lime-silicate rocks belong probably to the pyroxene-hornfels metamorphic facies.

In this part of Sulcis the sulfidic ores are often found together with these lime-silicate rocks and consequently almost all mining work is concentrated in these rocks.

Spotted slates

The slates of the eastern part of the investigated area are spotted and proceding to the granite of M. Arcosu and M. Lattias the slates become hornfelses with muscovite, andalusite and cordierite. Along the road from Siliqua to Acquacadda spotted Ordovician slates and spotted Cambrian slates (Cabitza) are exposed (fig. 50). It is clearly seen that the slates which underwent this metamorphism are more compact than the unattacked rocks. It is very difficult to determine of what mineral or minerals these spots consist as they are in an advanced stage of decomposition, but it seems very probable that the spots contain cordierite. Sometimes they show beautiful idiomorphic boundaries.

Bosma (1964) studied the spotted slates of the Vosges and Saxony and he considers the spots in those areas as pseudomorphs after cordierite with pseudohexagonal boundaries. The spots from the Sulcis rocks resemble those described by Bosma, but an extensive study would be necessary to establish their true nature.

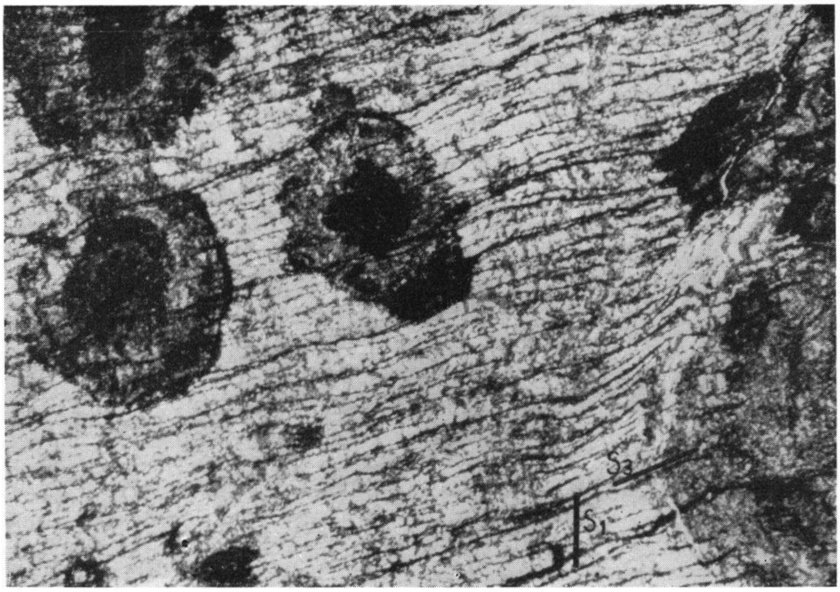


Fig. 50 Spotted slates of the Cabitza Formation formed by contact metamorphism by the Hercynian granite intrusion. Locality co-ord. 36,7 — 78,9. //-nicols (25 ×)

ORES

Introduction

The ores of Sardinia were already well known before Roman times and since then several deposits of different ore minerals were exploited. The galena and sphalerite deposits of south Sardinia are the most important from Italy. In north Iglesiente the lead-zinc mines are situated near the Arbus granite. The ore deposits there are mostly found in large quartz dykes committed to this granite. In south Iglesiente and in Sulcis almost all deposits are found in the upper part of the Metallifero limestones of Middle Cambrian age. In Sulcis only galena, sphalerite, chalcopyrite and barite are of economic value. Other ore minerals found in these deposits occur in very small quantities and are therefore economically insignificant.

Many authors described the ores during the last sixty years. Most of these publications are superficial and are based on a few observations only. Almost all authors consider these deposits as epigenetic, bound to the Hercynian orogeny. Within recent years, however, some German geologists (Wilke, Ehrendreich, Münch & Siebdrat, 1961) have described the lead-zinc ore deposits as syngenetic ones of Cambrian age. Zuffardi (1965) showed nice sedimentary structures in Iglesiente ores and at least those deposits are most probably of Cambrian syngenetic origin.

As director of the Rosas mines, Borghesan studied the ore deposits of that area. An extract of his description of these ores (1942) is as follows: "lenses of sulfides, mainly galena, sphalerite and small chalcopyrite concentrations. The deposits are formed under pneumatolytic to pyrometasomatic conditions. The sphalerite has a dark colour ("marmatite") and a rapidly changing FeS content. Gangue minerals are calcite, diopside-hedenbergite and sometimes garnet and quartz. The mineralization is mainly found on the limestone-slate contacts. The depth of oxydation depends on the structures. The mineralization of the Orbai and the Giuenni mines (resp. co-ord. 43 — 75,7 and 41,8 — 69,5) show less magmatic action".

The purpose of this chapter is to make a small contribution to the knowledge of the Sulcis ores on the basis of field data and an analytical study of about thirty samples.

Sulfides

To decide whether the sulfidic ore deposits are remobilized syngenetic or epigenetic deposits we have to consider some problems. The observations made in the field and in the laboratory are mentioned in the discussion of the following questions:

1. Are the ore deposits stratigraphically tied or not?
2. Do the limestone fragments in the basal conglomerate of the Ordovician contain this mineralization and the groundmass not?
3. What is the age relation between ore and surrounding rock?
4. What is the degree of metamorphism of the host rock and how does one distinguish a remobilized syngenetic ore deposit from an epigenetic one?
5. Is there a genetic relation between the ores and the basic dykes one often finds near the mineralization?
6. Is there a genetic relation between the ores and the volcanic products (tuffs) intercalated in the Lower Palaeozoic sediments?
7. Which ore minerals indicate a syngenetic origin and which an epigenetic origin of the deposits?
8. What are the temperature conditions under which the sulfidic ore minerals crystallized?

ad 1. — The ore deposits in Sulcis and part of Iglesiente are almost completely tied to limestone and dolomite or metasomatic transmutations of these rocks. As almost all limestones and dolomites in this area belong to the Metallifero Formation of Middle Cambrian age, one can say that the ores, found in this Formation, are more or less stratigraphically tied. However, in the limestone and dolomite beds intercalated in the top of the Arenarie Formation (Santadi area) and in the small limestone beds intercalated in the slates of the lower part of the Ordovician deposits (Rosas area), the same mineralization occurs. Consequently the conclusion is, that the ore deposits are tied to different stratigraphic horizons or still better not stratigraphically tied, but "lithologically" tied.

Both syngenetic and epigenetic ore deposits can be found in this way in limestone layers. The occurrences in the limestone are irregular. A good recognizable bedding plane generally fails, but often a kind of banding, that corresponds with the cleavage direction of the third phase (s_3), is seen. The ores often are concentrated on tectonic directions and in those cases not parallel to the bedding. On a large scale, however, the mineralization is parallel with the contact of Metallifero and Cabitza.

This question gives no decisive answer about the origin of the ore deposits.

ad 2. — An important point in the argumentation concerning the existence of Cambrian ores is the question whether or not fragments of the Ordovician basal conglomerate are mineralized and the groundmass not. A few years ago German ore geologists made an extensive survey in several Iglesiente mines and they studied this particular question about the conglomerate fragments. They found indeed limestone fragments with traces of ore minerals and came to the conclusion, that this mineralization was already present in the limestone fragments at the time of the conglomerate sedimentation and consequently the age of this mineralization is pre-Ordovician and presumably Cambrian.

There are some objections against this argumentation:

a) It is a possibility that the ore minerals found in the limestone fragments of the conglomerate are supplied after the sedimentation of the conglomerate. Ore bearing solutions can circulate through this rather permeable (fracture cleavage!) conglomerate. The limestone fragments form a kind of sponge in which the solutions intrude and the ore minerals crystallized. The groundmass of the conglomerate is pelitic (slate) and we have already seen, that the ores show a definite affinity to limestone. It is therefore not remarkable, that traces of ore minerals are not found in the slaty groundmass. Furthermore we deal with traces of ore minerals and only an extensive analysis of the limestone fragments on the one side and of the slaty groundmass on the other can establish a difference in ore mineral quantity between these two.

b) If the limestone fragments are mineralized and if it is clear that this mineralization is pre-conglomerate, the only conclusion one can draw is that a pre-Ordovician mineralization exists. It is furthermore very improbable, that one can establish the genesis of the ore minerals from the mineral occurrence in a few conglomerate pebbles.

ad 3. — The age of the host rock of the ore minerals is in almost all cases Middle Cambrian. Exceptions are the mineralized Ordovician limestone beds from the Rosas area and the mineralized Hercynian quartz dykes from northern Iglesiente.

The model ages of the lead of some galena samples collected (in co-operation with Prof. Ing. P. Zuffardi, Cagliari) from different mines in Sulcis and Iglesiente are determined by the "Laboratorium voor Isotopen-geologie" (Amsterdam). The lead-isotope compositions (in at. %) and lead model ages are listed below:

	204*Pb*	206*Pb*	207*Pb*	208*Pb*	age[1]
1. Min. Giuenni (Sulcis)	1,3750	24,7089	21,5220	52,3941	615 ± 60 M.A.
2. Monte Poni (Iglesiente)	1,3871	24,6765	21,4870	52,4584	590 ± 60 M.A.
3. Montevecchio (Iglesiente)	1,3641	24,8764	21,3661	52,3934	435 ± 40 M.A.
4. near Campanasissa (Sulcis)	1,3653	24,8385	21,3059	52,4904	400 ± 40 M.A.

The galena samples from Min. Giuenni (N-Sulcis) and Monte Poni (S-Iglesiente) indicate almost the same lead model age: i.e. an average of 610 ± 60 million year (M.A.). The galena from Montevecchio (N-Iglesiente) and a small deposit NE of Campanasissa (N-Sulcis, co-ord. 41,4 — 82,3) indicate younger model ages: i.e. an average of 420 ± 40 million year. In the best case the model age of lead represents the moment of separation from uranium and thorium with which is was associated in the mother rock. This particular moment does not necessarily coincide with the moment of deposition of the ore from which the sample has been taken.

[1] Lead model age, Holmes-Houtermans equation, 1960

$\lambda(238_u) = 1{,}54 \times 10^{-10}\ \text{yr}^{-1}$

$\lambda(235_u) = 9{,}72 \times 10^{-10}\ \text{yr}^{-1}$

$206_{Pb}/204_{Pb} = 9{,}50$ (at. %) }
$207_{Pb}/204_{Pb} = 10{,}36$ (at. %) } for lead of meteoritic origin

$238_u/235_u = 137{,}8$ (at. %)

age of lead development system $= 4{,}5 \times 10^9$ yr (age of earth's crust)

Many ore deposits are rejuvenated deposits, which means older deposits that are mobilized and recrystallized in more recent times. The ore deposits in Sulcis and Iglesiente are without doubt much younger than 600 million years, which indicates that we deal with a rejuvenated older deposit. Besides the four lead model age determinations mentioned above, another three are known from Sardinia. These analyses, reported in Rankama's "Progress in Isotope Geology" (1963-p. 437) are as follows:

	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	lead model age
5. Monte Poni	1,00	17,92	15,72	38,18	685 ± 70 M.A.
6. Monte Poni	1,00	18,10	15,87	38,53	690 ± 40 M.A.
7. Monte Poni	1,00	18,37	15,71	38,66	320 ± 50 M.A.

Determination no 5 is by Ehrenberg and Horlitz; no 6 and 7 by Eberhardt, Geiss and Houtermans. No 5 and 6 indicate a late Precambrian age but no 7 is obviously Hercynian. According to Zuffardi (pers. comm.) there are two possibilities to explain the Hercynian age of the third sample:

a) this sample came from Montevecchio instead of Monte Poni, or
b) during the Hercynian remobilization of the older ore deposits, some new lead generated from the Hercynian magma and came into the rejuvenated deposits.

Both explanations are possible but one thing seems very probable: whether sample 7 came from Montevecchio or from Monte Poni, at least two lead types of different model age occur in SW Sardinia (± 620 M.A. and ± 320 M.A.).

It is possible but improbable that the average model age of sample 3 and 4 (420 M.A.) indicates a separate lead generation between the late Precambrian — early Palaeozoic model age group and the Hercynian. It is possible by rejuvenation, that lead of some deposits contaminates with older or younger lead. This is a phenomenon which can be responsible for the differences in isotopic composition of the lead.

Hence, the conclusions one can draw from the model age determinations are:

a) at least two different groups of lead occur; a late Precambrian (early Palaeozoic) model age group (550—700 M.A.) and a Hercynian one (320 M.A.).
b) the late Precambrian (early Palaeozoic) galena deposits are rejuvenated by the Hercynian orogeny and the lead partly contaminated with newly generated Hercynian lead.
c) the ore deposits, as we find them now, are composed either of rejuvenated Precambrian (epigenetic?) ore minerals, or rejuvenated Cambrian syngenetic or Cambrian epigenetic (Sardic, early Caledonian?) ore minerals. Part of the ore minerals (Montevecchio) are at least partly Hercynian.

id 4. — At microscopic examination of the polished sections of the ore samples some striking phenomena indicating high temperature conditions during the crystallization are found. Most probably the ore deposits are formed under meso- to hypothermal conditions according to Lindgren's definition. The limestone of the Metallifero Formation is in a low stage of marmorization, due to regional metamorphism. In the field one often finds the ore minerals in the vicinity of lime-silicates. In northern Sulcis almost all lime-silicates are found in the Rosas area just as the ore deposits. This combined occurrence is obvious in the field, but exceptions are found.

The degree of metamorphism of the lime-silicates and the temperature of the ore bearing solutions agree with each other; wollastonite, andradite, diopside-hedenbergite, etc. (skarn-paragenesis) in the lime-silicates and high temperature indications in the ore minerals. The most acceptable conclusion one can draw is that the solutions responsible for the transformation of the limestone supplied the ore minerals.

The most likely place for mineralization is the top of the limestone sequence under the overlying slates. In this zone the most likely places are fracture zones (mostly parallel to the fracture cleavage s_3) and hinge zones of the minor folds, which is very well seen in the A.M.M.I. mines near Terrubia and Acquacadda (co-ord. 37,4 — 77,7 and 37 — 78,7).

However, so far as this combined occurrence of lime-silicates and ore deposits is concerned, the Rosas area forms an exception in Sulcis and Iglesiente. In most of the Iglesiente mines the lime-silicates are seldom found in large quantities related to the ore bodies. The same applies to the Giuenni deposits in Sulcis (co-ord. 41, 8 — 69,5), where lime-silicates are subordinate to the ores.

A plausible explanation for the combined occurrences of lime-silicates and ores is, that the deposits originally were poorly concentrated Cambrian syngenetic deposits, subsequently partly remobilized and concentrated by Hercynian meso- to hypothermal solutions. These solutions are at the same time responsible for the transformation of the limestone into a lime-silicate rock.

ad 5. — For many years geologists have wondered about the fact, that basic dykes (dolerites), more or less in an advanced stage of decomposition, are found together with ore deposits in the mines and in the field of Sulcis and Iglesiente.

Almost all authors in their discussion of this problem mentioned this relationship, but almost every one refuses to suppose a genetic relation between the ores and these basic dykes, which is very likely as:

a. the mineralization is never found in the dolerite bodies, but many times along the contact limestone — dolerite.
b. a genetic relation of galena and sphalerite with basic dykes has never been described.
c. in Sulcis and Iglesiente more and larger ore deposits occur than basic dykes and in some mines these basic rocks are absent.

The relationship between the dolerite and the ore deposits is only a spacial one, both mainly occurring on fracture zones along which repeated magmatic action took place. The dolerite intrusions came first, followed by ore bearing solutions (along the same supply courses) which are responsible for the forming of the lime-silicates and the partial decomposition of the dolerites.

ad 6. — In the sequence of Ordovician rocks of the Rosas area some thin tuff intercalations occur. The tuff beds are only a few decimetres thick and difficult to distinguish from slates, as they are folded and cleaved just as the slates.

Some supporters of the syngenetic origin theory of the ores consider these tuffs as the ore bearers and suppose part of the lime-silicates to be a mixture of tuffitic material and limestone (volcanic ashes sedimentated in a calcareous mud), but no such evidences are found by the present author. This, however, will not exclude the possibility of the occurrence of tuff horizons in the limestone, but they are not related with the ore deposits or the lime-silicates. The tuffs themselves are not ore bearing and removal of the ore minerals would certainly has left its traces. Above all there is much more ore than the few tuffs could contain!

ad 7. — The variety of ore minerals in syngenetic deposits is generally poor in contradistinction to epigenetic deposits. The ore deposits from Sulcis are neither poor nor rich in ore mineral variety. Probably more minerals occur as mentioned in this chapter, but only in small quantities.

The ore mineral paragenesis in the quartz dykes of northern Iglesiente (Montevecchio, Ingurtosu, Gennamari, etc.) is more comprehensive than the paragenesis in the deposits situated in the limestones. Lauzac (1964) described more than twenty different ore minerals of the Co, Ni, Bi, Ag and U paragenesis found in the quartz dykes, but these deposits probably contain two generations of ore: rejuvenated and newly formed (Hercynian).

Almost all the ore minerals found in Iglesiente and Sulcis are known from both syngenetic and epigenetic deposits. The Bi-minerals found by Lauzac (1964) in northern Iglesiente and found by the present author in very small quantities in the deposits of northern Sulcis (Piazzale Martha, co-ord. 41,2 — 77,2 and opposite Gall.

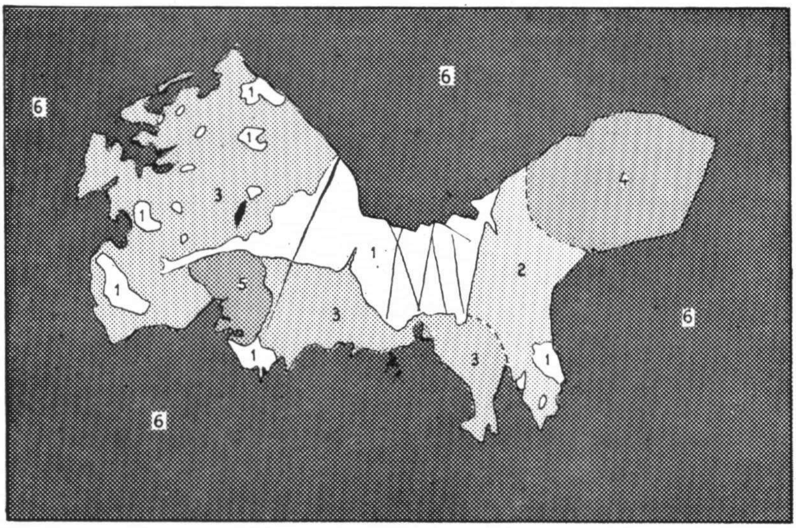


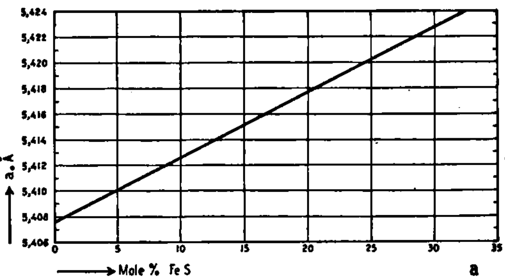
Fig. 51 Bismuth minerals in ore deposits of the Rosas area. 1. native bismuth, 2. bismuthinite, 3. chalcopyrite, 4, emplectite-klaprothite, 5. pyrrhotite, 6, sphalerite. Drawing after photograph. Locality co-ord. 39,8 — 76,1. (480 ×)

Sella, co-ord. 39,8 — 76,1) are almost exclusively known from epigenetic ore deposits (an exception: the "Mansfelder Rücken" deposits in Germany, which are closely related to the "Kupferschiefer"). The Bi-minerals from the Rosas area are: native bismuth, bismuthinite and emplectite-klaprothite (?). These minerals are almost always surrounded with sphalerite (fig. 51).

Other sulfidic ore minerals from the Rosas area are: galena, sphalerite, chalcopyrite, pyrite, marcasite, arsenopyrite, stibnite (locality co-ord. 36,4 — 72,3), pyrrhotite, tetrahedrite, boulangerite, bornite, chalcosite and covellite.

ad 8. — According to Borghesan (1936, 1942) the crystallization condition of the sulfidic ores of the Rosas area vary from epithermal (Min. Bega Trotta, co-ord. 39, 2 — 77,8) to pyrometasomatic with temperatures ranging from 600° to 1190° C. The same author mentioned a strong variation in FeS content of the sphalerites.

Kullerud (1953) extensively studied equilibrium relations of the FeS-ZnS system and showed that the rate of iron content of sphalerite is usable as a geological thermometer, provided that the sphalerite was formed under equilibrium conditions in the presence of an excess of iron, which may appear from the association of sphalerite with pyrrhotite. The solvus curve relating the amount of FeS that goes into solid solution in ZnS at different temperatures, was determined by Kullerud by means of the unit cell edge versus composition curve, but was proved not to be completely correct and a revision was made by Skinner, Barton and Kullerud (1959). Their new equation relating the cell edge ($\bar{a}_0$) of sphalerite to FeS content is a linear one (fig. 52a). The determinations of Kullerud (1953) and Skinner, Barton and Kullerud (1959) were performed at synthetic sphalerites.



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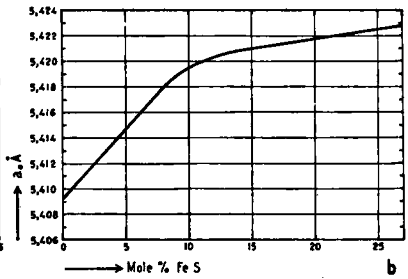

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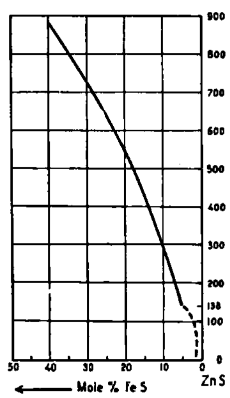

c

Fig. 52a Relation between unit cell size and composition of Fe-bearing sphalerites after Skinner, Barton and Kullerud (1959).

Fig. 52b the same relation after Krause (1961)

Fig. 52c Graph showing the composition of equilibrium β (Fe, Zn) S mix crystals as a function of the temperature after Kullerud (1953).

Krause (1961) studied natural sphalerites and arrived at a curve that goes approximately linear to 10 mole percent FeS, then deflects and continues less inclined (fig. 52b).

From the $\bar{a}_0$ values of the sphalerites of the Rosas area, determined by X-ray methods (Co-ray, Fe filter) and calculated by Mr R. O. Felius (Geol. Inst., Leiden), the mole percentages FeS are calculated according to the graph of Skinner, Barton and Kullerud and the one of Krause (resp. figs. 52a and 52b). The results of both methods and the matching temperatures according to Kullerud's diagram (fig. 52c) are as follows:

Sample	Locality	Co-ord.	$\bar{a}_0$	KRAUSE (1961) mole %	KRAUSE (1961) T	SKINNER, BARTON and KULLERUD (1959) mole %	SKINNER, BARTON and KULLERUD (1959) T
P 6327	sa Marchesa	37,5—77,7	5,4212 $\pm$ 0,0003	14,7—18,3	420°—530°	25—27	650°—680°
P 64120	sa Marchesa	37,5—77,7	5,41625 $\pm$ 0,00005	6,15— 6,3	160°—170°	15,1—15,3	435°—440°
P 6493	Leone	36,8—78,7	5,4143 $\pm$ 0	4,6	130°	10,96—11,04	320°—325°
P 6492	Leone	36,8—78,7	5,4166 $\pm$ 0,0002	6,3—6,8	170°—190°	15,5 —16,3	445°—455°
P 6491	Gannone	36,7—78,8	5,4200 $\pm$ 0,0001	10,8—11	320°—330°	23—24	605°—635°
P 6488	Gannone	36,7—78,8	5,4180 $\pm$ 0,0005	7,5— 8,5	230°—260°	18—20	525°—550°
P 6273*a*	Perda Carcina	41,05—75,1	5,4208 $\pm$ 0,0003	12,1—15,3	340°—440°	24—26	635°—655°
P 6273*b*	Perda Carcina	41,05—75,1	5,4204 $\pm$ 0,0001	9,7—18,1	290°—530°	21—27	560°—670°
P. 6273*c*	Perda Carcina	41,05—75,1	5,4212 $\pm$ 0,0003	14,7—18,3	420°—535°	25—27	650°—680°
P 6275	Perda Carcina	41,05—75,1	5,4187 $\pm$ 0,0002	8,6— 9	265°—290°	20—21	550°—565°
P 6462	Piazz. Martha	41,2—77,3	5,4166 $\pm$ 0	6,7	190°	16	450°
P 62121	Piazz. is Casiddus	40,8—77,8	5,4188 $\pm$ 0,0004	8,4— 9,3	235°—290°	20—22	550°—580°

The large differences between the calculations of the mole percentages and consequently the temperatures, are striking. The temperature range according to Krause's method is approximately from 130° to 475° C and according to the method of Skinner, Barton and Kullerud approximately from 320° to 665° C. Pressure corrections corresponding with the weight of the overlying rocks during the crystallization have to be made, but even then the temperature values are not reliable.

Based upon a chemical analysis of the FeS content of one of the samples (P 6275), it seems that the values obtained with Krause's graph are also inaccurate.

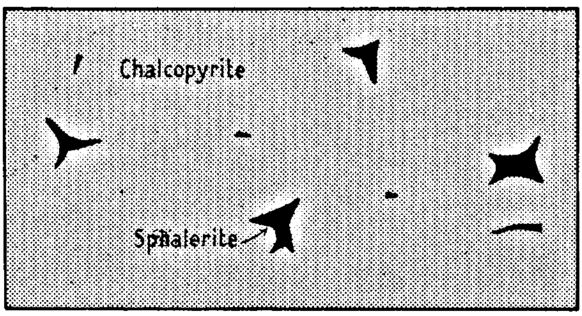

Fig. 53 Star shaped exsolution specks of sphalerite in chalcopyrite of sa Marchesa mine. Locality co-ord. 37, 5—77,7. (500 ×)

The colour of sphalerite is generally indicative about the crystallization temperature. It is obvious that the sphalerites with the lowest FeS percentage (P6493, P64120, P6492 and P6462) are transparent with a light yellow colour; while the sphalerites with a higher FeS content are dark brown coloured. If we examine the polished sections of the same samples microscopically, the differences between the sphalerites and the chalcopyrites of the different deposits are clear. The sphalerite with the highest FeS content and the darkest colour shows many chalcopyrite exsolution drops and the chalcopyrite of the same samples show star-shaped exsolution specks of sphalerite (fig. 53). About this last phenomenon Ramdohr (1960, p. 495) wrote: "Zinkblendesternchen sind durchaus beschränkt auf Lagerstätten hoher Bildungstemperaturen." The sphalerite with the lowest FeS content and the light yellow colour shows no exsolution phenomena and neither do the chalcopyrite of the same samples.

Besides these exsolution phenomena, the FeS content and the colour of the sphalerite, there is another high temperature indication: i.e. the exsolution of pyrrhotite in sphalerite and chalcopyrite. In the polished sections of the "high temperature" sphalerites (dark colour, high FeS content, chalcopyrite exsolution drops) small idiomorphic crystals of pyrrhotite are found. Ramdohr (1960) ascribed this phenomenon to a high temperature condition. The presence of pyrrhotite in spalerite signifies that the Fe content of the sphalerite was high.

Based on the facts of the varying FeS contents and colours of the sphalerite and the almost combined occurrences of ores showing no exsolution phenomena beside ores strongly showing these phenomena, the conclusion is that these ore minerals crystallized under different and rapidly changing conditions. A likely explanation for these rapidly changing conditions is the short distance of these deposits from the Hercynian granite, which intruded most probably to a comparatively small depth under the surface close to the ore bearing layers. The consequence of such an intrusion is a rather steep temperature gradient, which causes remobilization of the preexisting ore minerals and probably a supply of new minerals under rapidly changing conditions.

A quantitative analysis of a number of elements of some ore samples is made (by Holmetal, Billiton) and the percentages are listed below.

	P 6275 P. Carcina	P 6327 sa Marchesa	P 6462 Piazz. Martha	P 6480 near Gall. Sella
Sn	0,044	0,053	0,058	0,058
Pb	18,50	10,84	21,51	0,65
Cd	0,15	0,31	0,45	0,48
Zn	14,55	30,75	37,15	50,90
Ag	0,023	0,018	0,038	0,018
Bi	0,005	0,005	0,085	0,65
In	0,004	0,004	0,004	0,004
Mn	1,2	0,36	0,25	0,32
Hg*	0,001	0,001	0,001	0,001

* Less than

Obviou˙ are the high Bi percentages of the samples P6480 and P6462. From both occurrences Bi minerals were also found in polished sections.

The final conclusions about the ores of the Rosas area are:

The ore deposits of the Rosas area are produced by rejuvenation of older ore minerals by hydrothermal and pneumatolytical action during the Hercynian orogeny, partly together with newly generated ores (Hercynian) especially in northern Iglesiente (Montevecchio). The older ore minerals are:

a. late Precambrian (epigenetic?),
b. Cambrian syngenetic (metalliferous volcanic exhalations in sea?), or
c. early Caledonian (Sardic?) epigenetic.

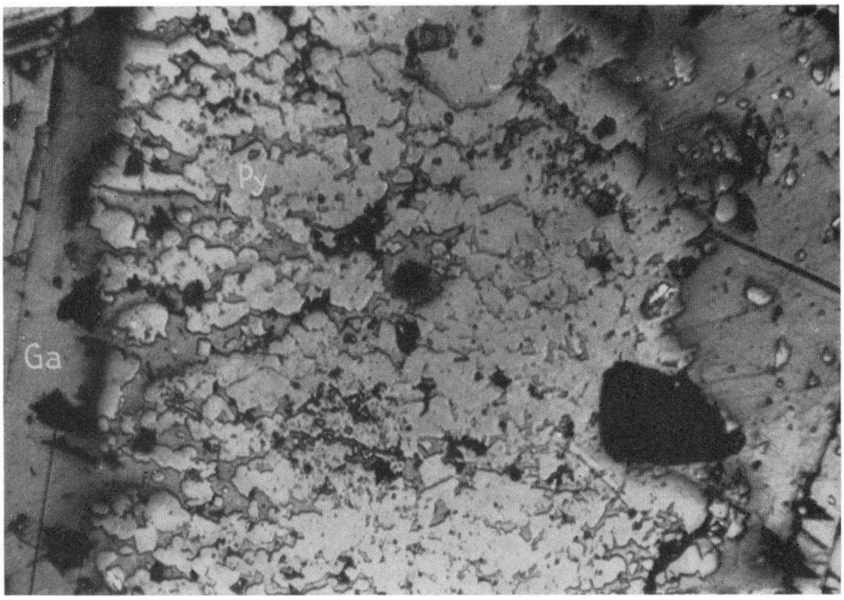

Fig. 54 Pyrite (Py) replaced by galena (Ga) in Giuenni ore deposits. Locality co-ord. 41,8 — 69,6. (12,5 ×)

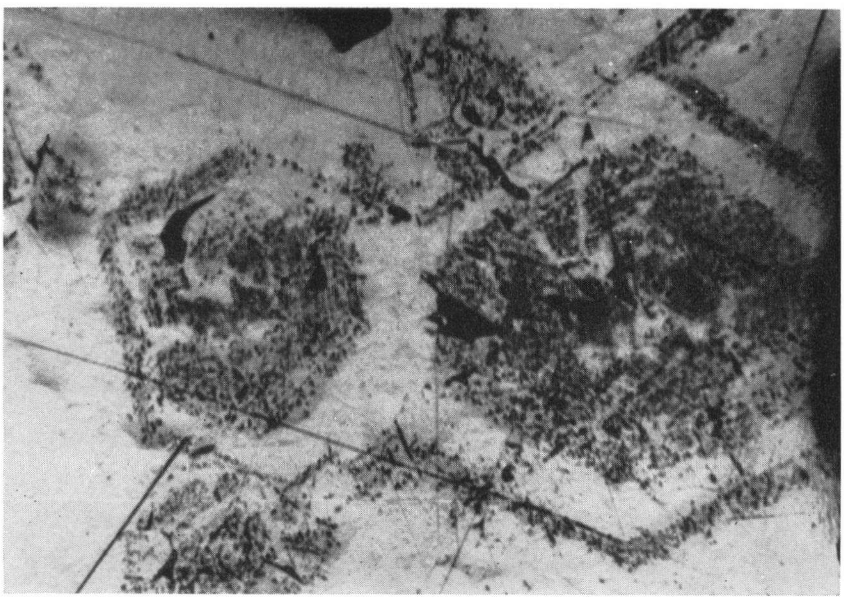

Fig. 55 Hexagonai pattern of carbonate inclusions in galena of Gall. Sulcis. Locality co-ord 39,4 — 77,5. (17,5 ×)

It is difficult to decide whether possibility a or b is the most probable one; c is very improbable.

During the Hercynian remobilization, the ores were mostly concentrated on tectonically predisposed places as fracture and cleavage systems and fold hinges (mostly third phase structures).

Non sulfides

Beside the important sulfidic ore deposits other ore minerals and even ore deposits occur, of which barite is by far the most important. Countless, but small, superficial excavations for barite are made in Sulcis and Iglesiente. The barite deposits in Sulcis are almost completely restricted to the limestones and dolomites of the Metallifero Formation, but exceptions occur. The barite concentrations are almost always found on tectonically predisposed directions as fracture zones. The exploitation is mainly done in very small concessions by the population of the nearby villages. Only in a few places are the deposits large and rich, so that exploitation on a larger scale is possible (Min. M. Ega, co-ord. 37,4 — 72,2). Promising concentrations are also found in the region of C. Margani (co-ord. 41,1 — 69) and in the M. Scorra area (co-ord. 42,3 — 72,8).

The colour of the barite is milky white and the barite is of a high quality, as little or no other minerals occur in these deposits. Regularly, but in very small quantities, galena is found together with barite. At some places barite-filled fractures cut through sulfidic ore deposits. This indicates that barite is younger than those sulfide deposits.

An interesting type of secondary ore concentration is found in some places on the plane south of the village of Terreseo (co-ord. 38,3 — 67,2). In the red-coloured weathering soil, small eluvial concentrations of yellow barite crystals occur.

A simple way to find the barite deposits in northern Sulcis is to follow the fracture zones in the limestones and dolomites of the Metallifero Formation (see map, scale 1 : 25000).

Other ore minerals found in northern Sulcis are economically insignificant as their concentrations are poor and the deposits small. They concern mainly the two mineral groups:

a. oxides: limonite, haematite and magnetite. In a few places limonite is exploited on a small scale.
b. carbonates: cerussite, malachite, azurite, smithsonite, rhodochrosite and probably some other carbonates. These carbonates are found together with the sulfides of the Rosas area and especially in the Truba Niedda — Bega Trotta deposits (co-ord. approximately 39,4 — 77,5).

EXCURSIONS

EXCURSION I

Start and finish Rosas, route approximately 12 km long, duration about 5 h. Requirements: geological map, scale 1 : 100000 (1938) and the present geological map scale 1 : 25000 (1965).

This route takes us mainly along outcrops of Cabitza slate, and conglomerate and slate of the Ordovician (fig. 56). In several outcrops one can find structures caused by the different folding phases and one can study the mutual relationship of these deformations.

Leave the car in front of the post office in Rosas and walk to no. 1.

1. Synclinal fold of Metallifero limestone, due to one of the first two E-W folding phases (fig. 18). This is one of the very few outcrops of Metallifero limestone in the neighbourhood, while just below the surface several galleries are cut in the limestone, which indicates a large limestone body beneath. The complex of Ordovician slate, lying unconformably on the limestone, is rather thin here and the Cabitza is absent.
2. Pta Susanna: Characteristically laminated Cabitza slate, strongly folded in very small folds by the third phase. The cleavage of this phase, at the same time axial plane cleavage of these folds, strikes NE-SW in this area and is at several places

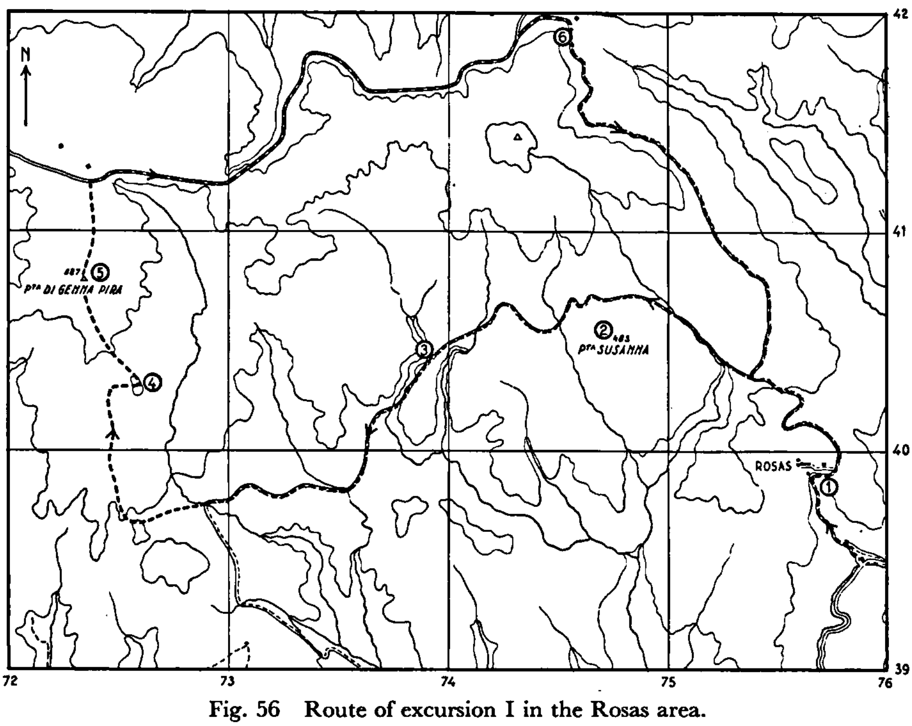

Fig. 56 Route of excursion I in the Rosas area.

refolded by the fourth phase. NE of the Pta Susanna the basal conglomerate (quartz conglomerate here) rises clearly above the terrain. The difference in intensity of deformation between the Ordovician slate along the road between the localities 1 and 2, and the Cabitza slate on the Pta Susanna is obvious.

3. In the surroundings of this locality one can study the transition from Cabitza slate to conglomerate and slate of the Ordovician, at various places. About 150 m beyond this locality one clearly sees from the road the δ_3-lineations on the s_3 planes at the opposite side of the valley.
4. This locality is the best place to examine the border zone of the Cabitza dome, by making some cross sections through the contact (fig. 6). It is clear that this structure is a real dome due to cross folding (second and third folding phase) and not an "erosion window".
5. From the top of the Pta di Genna Pira, looking SSE, one has a clear view of the northern part of the Cabitza dome we just visited. The steeply dipping light coloured Ordovician quartz-conglomerates along the border are well seen from here. On the top and on the eastern flank of the Pta di Genna Pira one can find many interesting structures as domes, basins, etc. due to successive folding by the second (E-W), third (N-S) and fourth (NW-SE) folding phase. The best recognizable fracture cleavage (s_3) normally strikes N-S, but is sometimes refolded by the fourth phase with a new coarse axial plane crenulation cleavage (s_{4a}).
   In this area many small conglomerates of both types are found (quartz- and slate-conglomerate). These conglomerates belong to the "basal zone" consisting of an alternation of conglomerate and slate. From the Pta di Genna Pira following the road to locality 6, one passes the contact Cabitza slate- Ordovician slate, here without conglomerate. The base of the Ordovician slates is mostly purple-coloured with elongated and steeply dipping light green-coloured reduction spots and stripes on the s_3 planes.
6. From the depression saddle between M. Rosas and M. Perd'e Quadda looking SE, one has a good view of the long and straight fault valley of the Riu de sa matta de Trexi. The M. Rosas consists of sandy slates, sandstones and micro-conglomerates which are folded with a N-S strike by the third phase.
   This is the last excursion locality. If you are thirsty and pass the shepherd (Mr. Zanda) who lives here, give him my regards. He will surely offer you some milk. From here half an hours walk takes us back to Rosas.

EXCURSION II

Start and finish Narcao, route approximately 20 km by motor-vehicle and 10 km by foot, duration about 7 h. Requirements: the present geological map, scale 1 : 25000 (1965). This route takes us along four different localities. In localities 1, 2 and 4 we will study structural phenomena, in locality 3 petrological. Between the localities one has to go by motor-vehicle.

From Narcao we follow the road to Acquacadda for about 2 km and leave the motor-vehicle near the small bridge over the Rio Canne. From here we walk northwards to locality 1a (fig. 57).

1a. Nicely developed minor to major folds in Arenarie sandstone and slate with axial plane fracture cleavage (s_3). Notice the ss-s_3 relation to decide on which side of the structure these outcrops are situated. The direction of these structures and s_3 is NE-SW.

b. Just a few metres in the small E-W valley, a minor anticline is exposed (fig. 24). Notice that the fold is similar (thickening in the hinges) and that the axial plane fracture cleavage (s_3) is fanning out. From these minor folds one can get information about the way of folding of the whole Arenarie area. From here we go back to our motor vehicle and return to Narcao. From Narcao we proceed along the road that passes the "campo sportivo" of Narcao to Cse Procaxius (2 km); fig. 58.

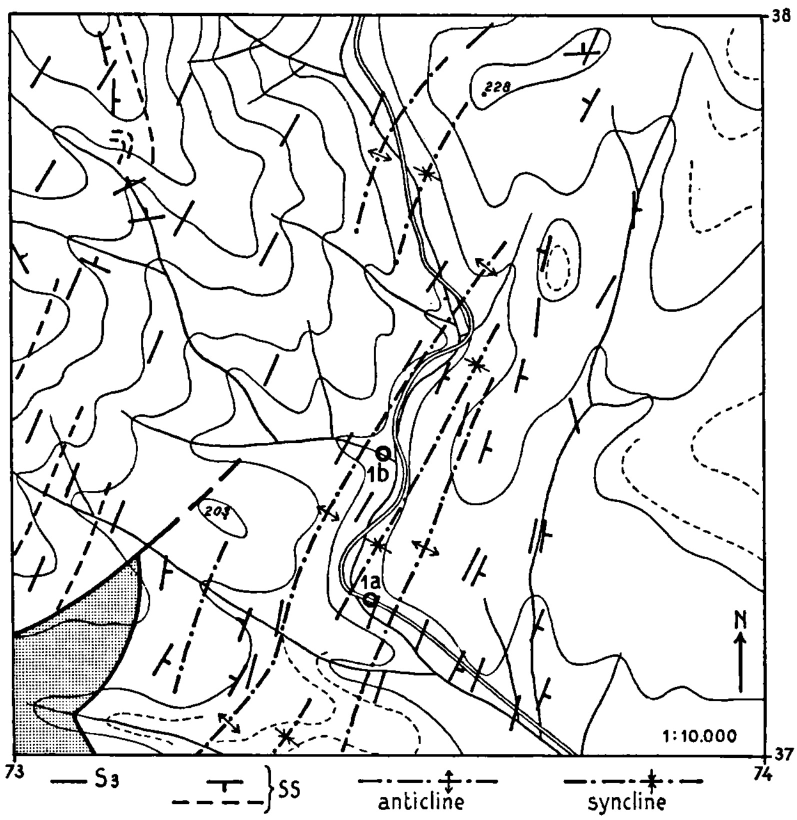

Fig. 57 Route of excursion II, east of Narcao.

2. In this area the Ordovician sequence does not start with one basal conglomerate, but with an alternation of conglomerate and slate with some limestone lenses. This area is gently folded by the second phase (E-W) and strongly refolded by the third phase (N-S). Of the original E-W structures nothing is left unless one looks for the δ_3-lineations (ss-s_3 intersections). At several places a steep δ_3 is found which indicates successive folding. The fourth phase did not deform this area, hence the steep δ_3-lineations are due to interference of the second and the third folding phase. In some outcrops one can observe on the most prominent fracture cleavage plane (s_3), the elongation axes of the pebbles and the δ_3-lineations together (fig. 31 shows these phenomena, but is of another locality). Nice exposures of these phenomena can be found between localities a and b. Near locality

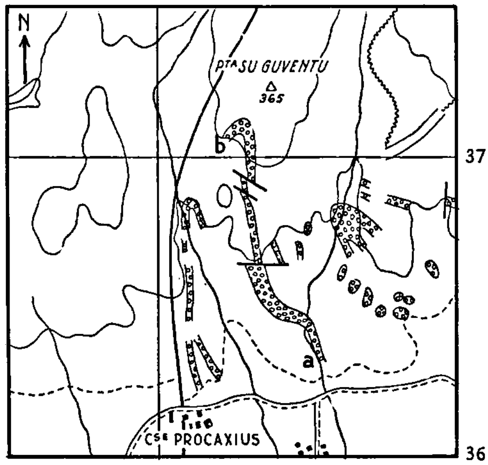

Fig. 58 Route of excursion II, west of Narcao near Cse Procaxius.

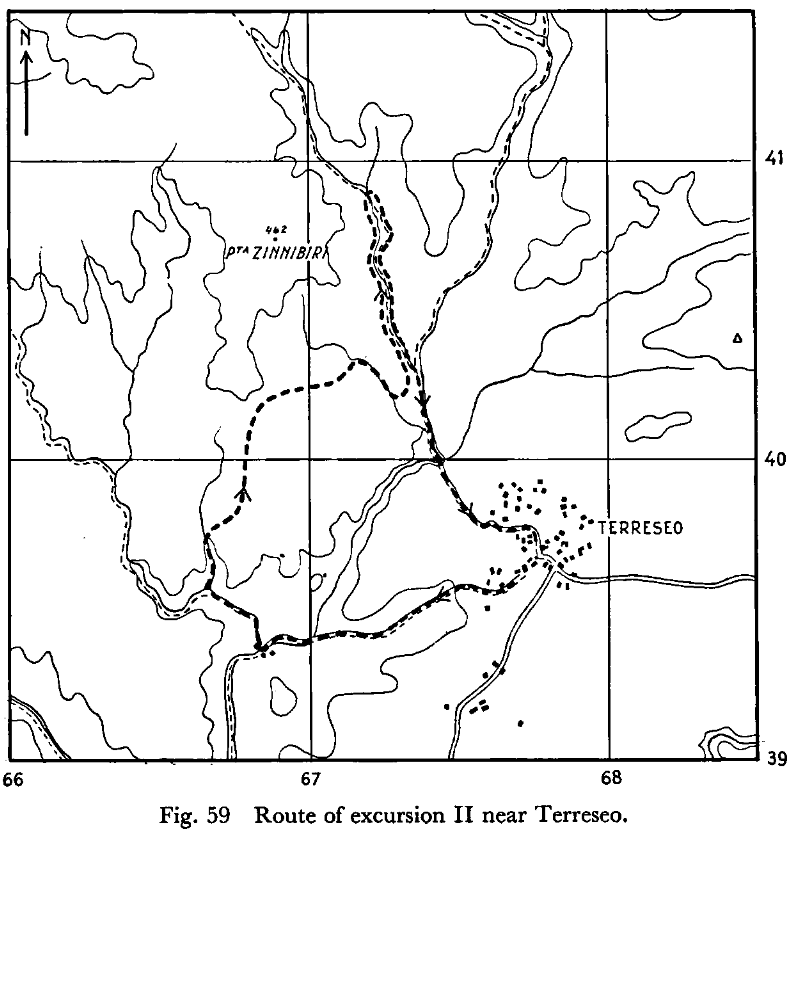

Fig. 59 Route of excursion II near Terreseo.

b a small outcrop of limestone and slaty limestone is exposed. From b we return to our starting point and continue our route via the village of Pesus to Perdaxius, turn to the north, pass Bingixedda and continue to M. s'Orcu (co-ord. 37,6 — 66,5).

3. Volcanic tuffs and flows. The tuff contains many limestone fragments (fig. 46), the flows are light-coloured, well layered, glassy rocks with nice flow structures (fig. 47). On the western slope of the M. s'Orcu an alternation of these rock-types is exposed. From the orientation of these volcanic layers and the orientation of the surrounding limestones, it is seen that the former are lying unconformably on the latter. From the special position of these volcanic rocks around the granodiorite stock of M. s'Orcu, it is concluded that the granodiorite is the pipe of an ancient volcano.
   After visiting this border zone of M. s'Orcu we return to Perdaxius and take the road in the direction of Pesus. After half a kilometre we turn to the north and proceed along Fattoria Mitza Justa to Terreseo.
4. From Terreseo we walk along the path to the SW. Directly west of the water installation, a small andesitic dike is found in the slaty-limestone. Follow the route as indicated in fig. 59. The s_3-crenulation cleavage in the Cabitza slates strikes N-S, but proceeding along the route one can notice the gradual swinging of the strike from N-S to E-W in the slates north of Terreseo. This large and unusual structure of the cleavage is not due to later deformation, but originated in this form as is explained in this paper (fig. 29). From Terreseo back to Narcao via Villascrua.

EXCURSION III

This excursion consists of visits to two separate outcrops, both showing the Cambro-Ordovician unconformity. Requirements: geological map, scale 1 : 100000 (1938) and the present map, scale 1 - 25000.

a. Locality along the road Siliqua-Acquacadda (co-ord. 41,7 — 82,5). The unconformity, west of the road, is not observable in one outcrop, but obvious if one compares the moderately folded, characteristically laminated, Cabitza slates along the road and the only very gently dipping Ordovician rocks above the railway.
b. Locality immediately west of Villamassargia and north of the road Villamassargia-Carbonia (co-ord. 47,7 — 68,3). This is the best place to study the unconformity in the mapped area. The best outcrop is situated along the brooklet near the small concrete stowage, about 100 m from the confluence with the Acqua Salia (fig. 8, and 9).

RIASSUNTO

Nella zona ricorrono arenarie, calcari e argilloscisti del Cambriano, ricoperti in discordanza da argilloscisti siluriani; entrambe le serie sono intruse da granodioriti e doleriti erciniche e da andesiti alpine.

Si adottano qui, come unità formali, le suddivisioni stratigrafiche tradizionali delle formazioni sottostanti la discordanza ordoviciana, e cioè:

Gruppo Iglesiente	Formazione di Cabitza	
	Formazione del Metallifero	Membro dei Calcescisti Membro dei Calcari Membro delle Dolomie
	Formazione delle Arenarie (base non visible)	

Si possono distinguere gli scisti cambrici da quelli ordoviciani anche là, dove manca il conglomerato bassale. Di conseguenza va riveduta una parte della Carta Geologica ufficiale (scala 1 : 100.000, 1938).

Le rocce cambriche e ordoviciano-siluriane hanno subito rispettivamente quattro o tre fasi di deformazione, con conseguente sviluppo di scistosità di diverso tipo: scistosità vera ("slaty cleavage"), scistosità trasversale ("fracture cleavage"), e scistosità secondaria per micro-corrugamento di superfici di discontinuità ("crenulation-cleavage").

Le grandi pieghe ad asse E-O del Cambrico fase sarda, sono in parte di tipo concentrico (nelle rocce delle Arenarie e del Metallifero) e in parte del tipo simile (formazione di "slaty-cleavage" negli scisti di Cabitza).

La seconda fase, ancora ad asse E-O, ha portato ad un ulteriore esaltazione delle strutture della fase sarda, e coinvolsero rocce ordoviciane e siluriche.

La terza fase di deformazione (ad asse Nord-Sud) fu il grande corrugamento ercinico, accompagnato da "fracture-cleavage" e da "crenulation-cleavage".

La quarta ed ultima fase ercinica (NO-SE e NE-SO) produsse un sistema coniugato di pieghe e di clivaggio.

Ne derivò uno specifico schema strutturale (a domi, bacini, ecc.), in conseguenza delle interferenze fra questi sistemi di pieghe ("Schlingenbau").

Molte pieghe sono disarmoniche, conseguentemente a differenza nelle caratteristiche meccaniche delle formazioni cambriche. La discordanza cambro-ordoviciana è stata in parte obliterata per scivolamenti ("decollement") dovuti a pieghe disarmoniche soprastanti e sottostanti questo piano.

I calcari sono stati in parte metamorfosati a rocce calco-silicatiche, per effetto dell'idrotermalismo e della pneumatolisi ercinica, con formazione di interessanti tipi di skarn.

I depositi minerari (Pb, Zn, Cu, ecc.) sono quasi completamente connessi ai calcari della Formazione del Metallifero.

L'età secondo modello, valutata mediante la composizione isotopica del Piombo in campioni di galena della miniera di Giuenni (Sulcis settentrionale) e della miniera di Monteponi (Iglesiente meridionale), e cioè di due depositi della Formazione del Metallifero, è di 600 milioni di anni. Per i campioni della Miniera di Montevecchio, (Iglesiente settentrionale) e da un affioramento lungo la strada Siliqua-Acquacadda — depositi che ricorrono rispettivamente in un filone quarzoso ercinico, e in una roccia calco-silicatica cambro-ordoviciana — è, invece, di 400 milioni di anni.

Quasi tutti i depositi sono stati ringiovaniti durante l'orogenesi ercinica.

LITERATURE

ARTHAUD, F., 1963. Un exemple de tectoniques superposées dans le Paléozoique de l'Iglesiente (Sardaigne). C.R. Soc. géol. Fr., 9, p. 303—304.
BENZ, J. P., 1964. Le gisement plombo-zincifère d'Arenas (Sardaigne). Trav. Lab. Sci. Terre Ecole Mines, Nancy, p. 1—127.
BERTOLIO, S., 1895. Sur le massif volcanique de Siliqua. Bull. Soc. géol. Fr., 23, p. 437—465.
BONO, G. L. DEL, 1965. Tentativo di nuova interpretazione geotettonica e stratigrafia del Cambro-Ordoviciano nell'Iglesiente settentrionale. Nota prelim. Resoc. Ass. miner. Sarda, Fo. inform. soci, 1 p.
BORGHESAN, E. C., 1935. Giacimenti di misti galene e blende del tipo di metasomatismo termico di contatto fra intrusione basica e calcare. Resoc. Ass. miner. Sarda, 40, 6, p. 9—13.
—— 1936. Giacimenti di solfuri misti di pirometasomatismo in rocce calcaree nella miniera Marchesa (Narcao). Resoc. Ass. miner. Sarda, 41, 6, p. 205—217.
—— 1942. Miniere del gruppo Rosas (sa Marchesa, Begatrotta, Rosas, Mitza Sermentus). Resoc. Ass. miner. Sarda, 47, 3—4, p. 51—57.
BORNEMANN, J. G., 1886. Die Versteinerungen des Cambrischen Schichtensystems der Insel Sardinien. Nova Acta K. Leop. Carol. dtsch. Akad. Naturf., 51, 1, p. 1—147.
—— 1891. Die Versteinerungen des Cambrischen Schichtensystems der Insel Sardinien. Nova Acta K. Leop. Carol. dtsch. Akad. Naturf., 51, 3, p. 437—529.
BOSMA, W., 1964. The spots in the spotted slates of Steige (Vosges) and Vogtland (Saxony). Geol. en Mijnbouw, 11, p. 476—490.
BUCCA, L., 1888. Studio petrografico su alcune roccie dell'Iglesiente. In Zoppi, G., 1888. Descrizione geologico-mineraria dell'Iglesiente (Sardegna). Mem descr. carta geol. d'Ital., 4.
BURFORD, J. A., 1933. Les formations volcaniques de la Sardaigne. Schweiz. miner. petr. Mitt., 13, p. 366—397.
CADISCH, J., 1938. Zur Geologie der Insel Sardinien. Geol. Rundschau, 29, p. 52—72.
CAMERANA, E., 1899. Intorna all'origine del calcare metallifero dell'Iglesiente. Resoc. Ass. miner. Sarda, 4, 6.
Carta Geologica d'Italia, 1938. Fo. 233 (Iglesias), scale 1 : 100000, R. Uff. Geol., Roma.
CATALISANO, S., 1930. Il rilevamento geologico della tavoletta di Narcao (Foglio 233, Iglesias). Boll. R. Uff. geol. d'Ital., 55, 9, p. 1—18.
CAVINATO, A., 1937. Cenno su un'area metamorfica e sulla genesi e significato di una metallizzazione. Resoc. Ass. miner. Sarda, 42, 5, p. 165—192.
—— 1939. Epoche metallogeniche in Sardegna. Resoc. Ass. miner. Sarda, 44, 2.
—— 1948. Il profilo del cambriano e le mineralizzazione. Atti cong. miner. Ital., Ass. miner. Sarda.
CHINAGLIA, C., 1925. Formazione di eta incerta nel Sulcis. Resoc. Ass. miner. Sarda, 30, 8, p. 15—21.
CLOOS, E., 1947. Oolite deformation in the South Mountain fold, Maryland. Geol. Soc. Am. Bull., 58, p. 843—918.
COMASCHI CARIA, I., 1949. I fossili della Sardegna. Ist. studi Sardi.
COSIJN, D., 1965. Verslag van het karteringswerk van Giba en Santadi (Sardinië). Unpublished Drs thesis, Geol. Inst., Univ. Leiden, 12 p.
FERUGLIO, E., 1924. Sulla morfologia del Campidano in Sardegna. Boll. Soc. geol. Ital., 43.
FLEUTY, M. J., 1964. The Description of Folds. Proc. Geologists ass., 75, p. 461—492.
FRIETSCH, R., 1957. Determination of the composition of garnets without chemical analysis. Geol. Fören. Förhandl., 79, 1, p. 43—51.
GÈZE, B., 1952. Sur les rapports géologiques entre Languedoc et Sardaigne. Boll. Soc. geol. Ital., 71, p. 144—150.

Gortani, M., 1922. Osservazioni sul paleozoico della Sardegna. Boll. Soc. geol. Ital., 41, 4, p. 362—370.

Graulich, J. M., 1953. Osservazioni sulla scistosità nei terreni paleozoici dell'Iglesiente (Sardegna), significato dell'anagenite. Boll. Soc. geol. Ital., 72, p. 3—7.

Harker, A., 1960a. Petrology for students. Cambridge Univ. Press, London—New York, 283 p.

—— 1960b. Metamorphism. Methuen & Co., London; Dutton & Co., New York; 362 p.

Hatch, F. H. & Rastall, R. H. (rev. Trevor Greensmith, J.), 1965. Petrology of the sedimentary rocks. George Allen & Unwin Ltd., London, p. 221—235.

Havre, H., 1932a. Esquisse géologique de l'Iglesiente. Resoc. Ass. miner. Sarda, 37, 2—3, p. 17—25.

—— 1932b. Tectonique de l'Iglesiente. Resoc. Ass. miner. Sarda, 37, 7, 4—13.

Kluyver, H. M., 1965. Geologische kartering van twee gebieden in SW-Sardinië. Unpublished Drs thesis, Geol. Inst., Univ. Leiden, 20 p.

Knill, J. L., 1960. A classification of cleavages with special references to the Craignish district of the Scottish Highlands. Rep. 21st. internat. geol. Cong., Copenhagen, 18, p. 317—325.

Krause, H., 1961. Analytische und röntgenographische Untersuchungen natürlicher Zinkblenden. N. Jahrb. Miner., Abh. 97, p. 143—164.

Kullerud, G., 1953. The FeS-ZnS system, a geological thermometer. Norsk. geol. Tidsskr., 32, p. 62—144.

Lambert, G. B. A., 1896. Discussione sulla geologia e sulla tettonica dell'Iglesiente in rapporto allo studio dei giacimenti metalliferi. Resoc. Ass. miner. Sarda, 7, 4.

Lauzac, F., 1964. Sur l'existence de cinq formations métallifères dans le district plombo-zincifère du Sud-Ouest de la Sardaigne. C.R. Acad. Sci. Fr., 258, 8, p. 2363—2365.

Maccioni, L., 1964. I calcescisti di Sinibidraxiu. R.C. Seminair. Fac. Sci. Univ. Cagliari, 34, p. 82—93.

Marmora, A. F. della, 1857. Viaggio in Sardegna, III, Descrizione geologica. Edizione il Nuraghe, Cagliari, 1927.

Maxia, C., 1938. Metamorfismi e mineralizzazione nel Paleozoico dell'Oriddese (Sard. SO). R.C. Seminair. Fac. Sci. Univ. Cagliari, 8, 1.

Meneghini, G., 1888. Paleontologia dell'Iglesiente in Sardegna, Fauna Cambriana, Trilobiti. Mem. R. Com. geol. d'Ital., 3, 2.

Minucci, E., 1935. Le condizioni del Paleozoico nel Sulcis Orientale (Sardegna). Boll. Soc. geol. Ital., 54, p. 75—88.

Niggli, P., 1939. Tabellen zur Petrographie und zum Gesteinsbestimmen. Hiltpold, Zürich, 150 p.

Novarese, V., 1914. Il rilevamento delle tavolette di Iglesias e di Nebida. Boll. R. Com. geol. d'Ital., 44, 4, p. 49—75.

—— 1942. Sul Cambriano della Sardegna. Boll. R. Uff. geol. d'Ital., 67, p. 1—28.

Novarese, V. & Taricco, M., 1922. Cenni sommarii sul paleozoico dell'Iglesiente. Boll. Soc. geol. Ital., 41, 4, p. 316—326.

Pettijohn, F. J., 1956. Sedimentary rocks. 2nd. Ed., Harper & Bros, New York, 710 p.

Poll, J. J. K. & Zwart, H. J., 1964. On the tectonics of the Sulcis area, S-Sardinia. Geol. en Mijnbouw, 43, 4, p. 144—146.

Pompecky, J. F., 1901. Fossili dell' orizonte dei Paradoxides di Cabitza in Sardegna ed osservazioni sulla suddivisione del Cambrico Sardo. Resoc. Ass. miner. Sarda, 6, 8.

Ramdohr, P., 1960. Die Erzmineralien und ihre Verwachsungen. Akad. Verlag, Berlin, 1088 p.

Riva, C., 1898. Formazione diabasica di Rosas. Resoc. Ass. miner. Sarda, 2, 5.

—— 1899. Sopra la formazione diabasica e sopra alcuni minerali di Rosas nel Sulcis (Sardegna). Rend. R. Ist. Lomb., ser. 2, 32, 4.

Rossetti, V., 1946. I granati di Oridda (considerazione). R. C. Seminair. Fac. Sci. Univ. Cagliari, 16, 1—2.

Salvadori, I., 1961. Contributo alla conoscenza geomineraria del settore di Teulada. Resoc. Ass. miner. Sarda, 65, 9.

SALVADORI, I. & ZUFFARDI, P., 1961. Il giacimento di Monte Tamara (Sardegna). Resoc. Ass. miner. Sarda, 65, 7, p. 53—87.

SANDER, B., 1948. Einführung in die Gefügekunde der geologischen Körper, T. 1, Springer, Wien-Innsbruck, 212 p.

SCHWARZBACH, M., 1939. Das Normalprofil des sardischen Kambriums. Zentralbl. Min. Geol. Pal., Abt. B, p. 49—60.

—— 1952. Zur Stratigraphie des sardischen Kambriums. N. Jahrb. Geol. Pal., Mon.h., 2, 65—70.

SHROCK, R. & TWENHOFEL, W. H., 1953. Principles of invertebrate paleontology McGraw Hill, London-New York, p. 87—91.

SITTER, L. U. DE, 1958. Boudins and parasitic folds. Geol. en Mijnbouw, N. S., 20, p. 277—286.

—— 1964. Structural Geology. 2nd Ed., McGraw Hill, London-New York, 551 p.

SKINNER, B. J., BARTON, P. B. JR. & KULLERUD, G., 1959. Effect of FeS on the unit cell edge of sphalerite. A revision. Econ. Geol., 54, p. 1040—1046.

STILLE, H., 1939. Bemerkungen betreffend die "sardische" Faltung und den Ausdruck "ophiolithisch". Zeitschr. deutsch. geol. Ges., 91, p. 771—773.

TARICCO, M., 1912. Contributo allo studio del Cambriano della Sardegna in Sulcis. Resoc. Ass. miner. Sarda, 17, 2.

—— 1926. Gita geologica nel Fluminese ed osservazioni sul Paleozoico della valle del Cixerri. Resoc. Ass. miner. Sarda, 31, 5, p. 11—19.

—— 1928. Il Cambriano del Sulcis (Sardegna). Resoc. Ass. miner. Sarda, 33, 8, p. 10—29.

—— 1930. Sull'origine dei calcescisti cambriani della Sardegna. Boll. R. Uff. geol. d'Ital., 15, 2, p. 1—21.

TEICHMULLER, R., 1931. Zur Geologie des Tyrrhenisgebietes. Abh. Ges. Wiss., Göttingen, math. phys. Kl., 3, p. 1—124.

TESTA, L., 1914. Il terreno Carbonifero a sud di Monte Poni. Resoc. Ass. miner. Sarda, 19, 3.

TESTA, L. & SARTORI, F., 1917. Estensione del Cambriano a sud d'Iglesias. Resoc. Ass. miner. Sarda, 22, 7.

VALERA, R., 1964. Nuove osservazioni sui rapporti tra le orogenesi caledonica ed ercinica nel settore di Mte Murvonis a NE di Domusnovas (Iglesias). Resoc. Ass. miner. Sarda, 68, 6, p. 8—13.

VARDABASSO, S., 1940. Qual'è il profilo normale del Cambrico Sardo? Resoc. Ass. miner. Sarda, 45, 3, p. 100—110.

—— 1950a. Il problemo stratigrafico del Cambrico Sardo. Rend. R. Acad. Lincei, 9, 6.

—— 1950b. Osservazione geologiche sul Cambrico del Fluminese. Resoc. Ass. miner. Sarda, 54, 4, p. 27—34.

—— 1956. La fase sarda dell'orogenesi Caledonica in Sardegna. Geot. Symp. zu Ehren H. Stille, Stuttgart, p. 120—128.

—— 1960. Questions concerning the Caledonian era in Sardinia (Italy). Rep. 21st internat. geol. Cong., Copenhagen, Vol. Abstracts, p. 200.

WASHINGTON, H., 1914. The volcanic cycles in Sardinia. Resoc. Ass. miner. Sarda, 19, 5.

WILKE, A., EHRENDREICH, E., MUNCH, W. & SIEBDRAT, H., 1961. Montangeologische Untersuchungen in italienischen Blei-Zink-Erzbergwerken, a) im Debiet von Iglesias, Sardinien, b) in den Bergamasker Alpen. Zeitschr. angew. Geol,, Dtsch., 7, 5, p. 256.

ZABELLI, A., 1948. Studio sul Cambriano Sardo (tettonica e giaciture metallifere dell'Iglesiente). Atti cong. miner. Ital., Ass. Miner. Sarda., p. 275—296.

ZOPPI, G., 1888. Descrizione geologico mineraria dell'Iglesiente (Sardegna). Mem. descr. carta geol. d'Ital., 4.

ZUCCHINI, A., 1959. Brevi appunti sulla sedimentazione Cambrica nell'Iglesiente (Sardegna SO). Resoc. Ass. miner. Sarda, 63, 5—6.

ZUFFARDI, P., 1950. Il giacimento Piombo-Zincifero di Montevecchio, Sardegna. Rep. 18th internat. geol. Cong., London, 7, p. 266—277.

—— 1962. Contributo alla conoscenza delle mineralizzazioni nel Cambrico Sardo. Resoc. Ass. miner. Sarda, 66, 4, p. 7—28.

—— 1965. Strutture sedimentarie in talune mineralizzazioni paleozoiche sarde a solfuri. Resoc. Ass. miner. Sarda, 70, 5, p. 1—22.