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Ultramafics and Ophiolites: Record of a Visit to the Alps, Cyprus, France, and England

by

H.L. Davies

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SUMMARY

This is a record of a study of ultramafic and related rocks in Cyprus, France, England, and the Alps. Remarkable similarities in the rock types and structure of the ophiolites of the western and eastern Alps, the Troodos Complex in Cyprus, and the Papuan Ultramafic Belt (P.U.B.) in Papua-New Guinea, suggest that all have a common origin. Probably all are oceanic crust and mantle. Similarities between the Troodos Complex and the P.U.B. may help us in the search for ore minerals in Papua-New Guinea. The ultramafic fraction of all of these complexes is poor in Al_2O_3 and CaO and is probably refractory mantle, i.e. a residuum which remains when basaltic magma is generated by partial melting of primary mantle. However, the ultramafic rocks of the innermost western Alps contain significant CaO and Al_2O_3 and are probably primary mantle. It is puzzling that probable primary mantle at Lanzo in the western Alps and Lizard, Cornwall, is closely associated with gabbro. The terms ophiolite and alpine peridotite should be avoided in discussing Papua-New Guinea geology because there appears to be no general agreement, at least among English-speaking geologists, on their exact meaning.

INTRODUCTION

In March 1968 I was awarded a Commonwealth Public Service postgraduate scholarship to attend the International Geological Congress in Prague in August 1968, and to spend about twelve months at Stanford University in California. At Prague I was to take part in discussions on the earth's upper mantle, and at Stanford I was to complete a Ph. D., begun in 1963-4, with a dissertation on the Papuan Ultramafic Belt. The Overseas Travel Committee of the Public Service agreed to a proposal that I should inspect ultramafic rocks in Cyprus, France, and in the western Alps on my way from Canberra to Prague.

This is a record of that trip in narrative form. It includes some discussions of general interest, such as that under the heading "The ophiolite problem", and some observations pertinent to our work in Papua-New Guinea, as indicated in the table of contents.

The trip was scheduled to start on July 22, 1968. I took recreation leave and left Australia on July 11 so as to have time to visit the Malaysian Geological Survey and to extend my stay in Cyprus from the scheduled four days to a week. I was accompanied by my wife and child whose fares were partly met by the scholarship.

It was my first contact with European and, in particular, Alpine geology and the experience was very stimulating. It was an introduction to a style of geology and a field of literature with which I was unfamiliar, and which has many parallels in New Guinea. It was also an example of that best type of geological meeting, the field conference, which brings together geologists of various backgrounds to stand on an outcrop (better still a controversial outcrop) and exchange their views.

Acknowledgements

I am very grateful to Tom Thayer who invited me to join the Alpine tour, and to our hosts and guides on that tour: Professors Forestier, Vuagnat and Galli, Drs. Nicolas and Dal Piaz, and also our hosts at other points: S.K. Chung and S. Senathi Raja in Malaysia, A. Panayiotou in Cyprus, and J.S. Milsom in England. To Dale Jackson, Professors Van der Kaaden and Coombs, Messrs. Wicks, Piccardo, Bezzi, Lanier and the others of our party I owe a debt of friendship and stimulating discussion.

I want to express my appreciation of the Commonwealth Public Service scholarship which covered fares from Canberra to San Francisco, and expenses and salary from August 19 onwards, and the Overseas Travel Committee's approval for travel between July 22 and August 19. I owe thanks to Dr. N.H. Fisher and Mr. Bruce Williams of B.M.R. for assistance in planning and organizing the tour, and to Professors Ringwood of A.N.U. and Krauskopf of Stanford University, and again to Dr. Fisher, for supporting the scholarship application.

MALAYSIA (July 12-15)

Hosts and guides

Geological Survey of Malaysia, Opoh:

Chung S.K. (Director)
D. Santokh Singh (Assistant Director)

Geological Survey of Malaysia, Kuala Lumpur

S. Senathi Raja (Acting Principal Geologist)
Chong Foo Shin
T. Suntharalingam

Canada - Malaysia Colombo Plan Project, Kuala Lumpur

Geoff Allen, geologist
Paul Piazza, photogeologist

University of Malaysia, Kuala Lumpur

N.S. Haile, geology professor
C.S. Hutchison

Geological Survey of Malaysia

The headquarters of the survey at Ipoh are impressive: the office and laboratory building stands in a park-like setting partly surrounded by roomy two-storey houses for the geologists. Local work includes investigations related to tin and iron mining.

The Director of the Survey may soon move his headquarters to the federal capital, Kuala Lumpur. I spent a few hours in the Kuala Lumpur office, mostly hearing about the Canada-Malaysia Colombo Plan project.

Canada - Malaysia Colombo Plan project

The Canada-Malaysia Columbo Plan project is to map and geochemically test an area of 4,000 square miles south of 3° N latitude over a period of two years. It is staffed by five geologists of various nationalities employed by a Canadian prospecting company (formerly Huntings) under contract to the Canadian government, and by members of the Malaysian Geological Survey. One of the Malaysian geologists on the project is Chong Foo Shin (Eddie Chong) who spent some time with B.M.R. in Canberra and on the Bougainville survey. I was impressed by the enthusiasm of the young Malaysian geologists and their "Canadian" counterparts.

Paul Piazza, photo-geologist from New York, showed me some typical airphotos and gave a quick account of the geology of the area: a gently folded capping of Cretaceous sediments overlies more severely folded Triassic and older rocks, which are intruded by granite. The Cretaceous capping bears a distinctive stunted forest; the granite has a dense drainage pattern with many small landslides. Piazza has prepared photo-scale interpreted geological maps of the entire project area for use by the field parties.

There are I think four field parties, one Canadian and one Malaysian geologist in each, and each team is responsible for an area. Field techniques are like those that we have used in New Guinea. Most of the work is on foot, moving base camp every few days. Carriers are drawn from local villages but are retained through field breaks so that a more-or-less permanent labour force is maintained while in any one area. Field equipment is carried in small iron patrol boxes which are worn as a back-pack.

I raised the possibility of using helicopters and was told that natural landing sites are too few and far between. A quick glance at some airphotos of Eddie Chong's area confirmed this. Relief is generally too low for the development of major landslides or of gravel banks in the river, and all of the land area is forested. However helicopters could be harnessed at least to move teams to and from their field areas, assuming that finance and a suitable operator could be found. I intended to do a feasibility study of a typical area but there was not time.

University of Malaysia, Kuala Lumpur

Charles Hutchison showed me instrumentation which he has developed for thermoluminescence studies in limestone (Hutchison, 1968); in particular this includes a constant-temperature-increase oven (one degree C per second). He also showed me rock specimens from the basic igneous complex at Darvel Bay in Sabah (Kirk, in prep.; Hutchison and Donau, in prep.). Here he has found albite-amphibolite gneisses in an area previously mapped as gabbro. Professor Haile introduced me to other members of the teaching staff.

CYPRUS (July 16-24)

Hosts and people met

Geological Survey Department, Nicosia

Y. Hji Stavrinou, Director
Andreos Panayiotou
Georges Constantinou

U.N. Mission (groundwater and mineral resources)

Tornsquist, (leader), Sweden
R. Francken, Netherlands
D.L. Searle, Britain
P. Knoup, Switzerland
L.M. Bear, Britain, former Director of Cypriot Geological Survey.

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Narrative

The purpose of our visit to Cyprus was to examine the Troodos Complex which has features in common with the Papuan Ultramafic Belt. I was curious to see just how far this similarity went, and in particular, was hoping for clues which might lead us to sulphide mineralization of the Troodos type in Papua-New Guinea.

We arrived in Nicosia by prop-jet aircraft from Beirut; the central plains looked parched and dusty, and the shade temperature was 104°F. We were met by Andreos Panayiotou, geologist with the Cyprus Geological Survey Department, who was to be our guide and liaison for the length of our stay.

The Cyprus Survey is manned by a small group of Cypriot geologists under Director Y. Hji Stavrinou. Our stay coincided with the last stages of activity of a fourteen-man United Nations mission investigating groundwater and mineral deposits. Tornsquist was the leader, and Francken and Searle were in charge of the search for minerals so far as I could gather. Panayiotou had worked closely with Searle in the detailed mapping of likely sulphide prospects in the pillow lavas. Also attached to the mission was a former director of the Cypriot Survey, L.M. Bear, who has worked on the island for fifteen years.

Literature

The Geological Survey Department of Cyprus has an excellent series of publications on the geology of the island and we may expect that these will soon be augmented by results from the U.N. mission. For a guide to the geology of the entire island I was advised to consult Henson, Browne, and McGinty (1949). I found the 1:250,000 scale geological map of Cyprus invaluable; it was compiled by L.M. Bear and published by the Survey in 1963.

The best guide for a quick visit to Troodos is Geological Survey of Cyprus Memoir No. 1 by Wilson and Ingham (1959) in which Wilson describes the geology of the Troodos area which he mapped at 1:5000 scale; he incorporates some previous work by D.W. Bishopp and D.J. Burdon. Areas of interest are described in such detail that they can be easily relocated. The south-eastern part of the complex is described in detail in another G.S.C. Memoir (Pantazis, 1967). A resume of Troodos geology and gravity is given by Gass and Masson-Smith (1963) and Gass (1967, 1968), and a chemical-mineralogical study of the gabbro, granophyre, and basalt phases has been prepared by Bear (1966). In addition to these, an unpublished doctoral thesis by German student, Wolf Bottcher, was commended to me by the Mining Engineer at Skouriotissa, Mr. Oscar Kortan.

Geology

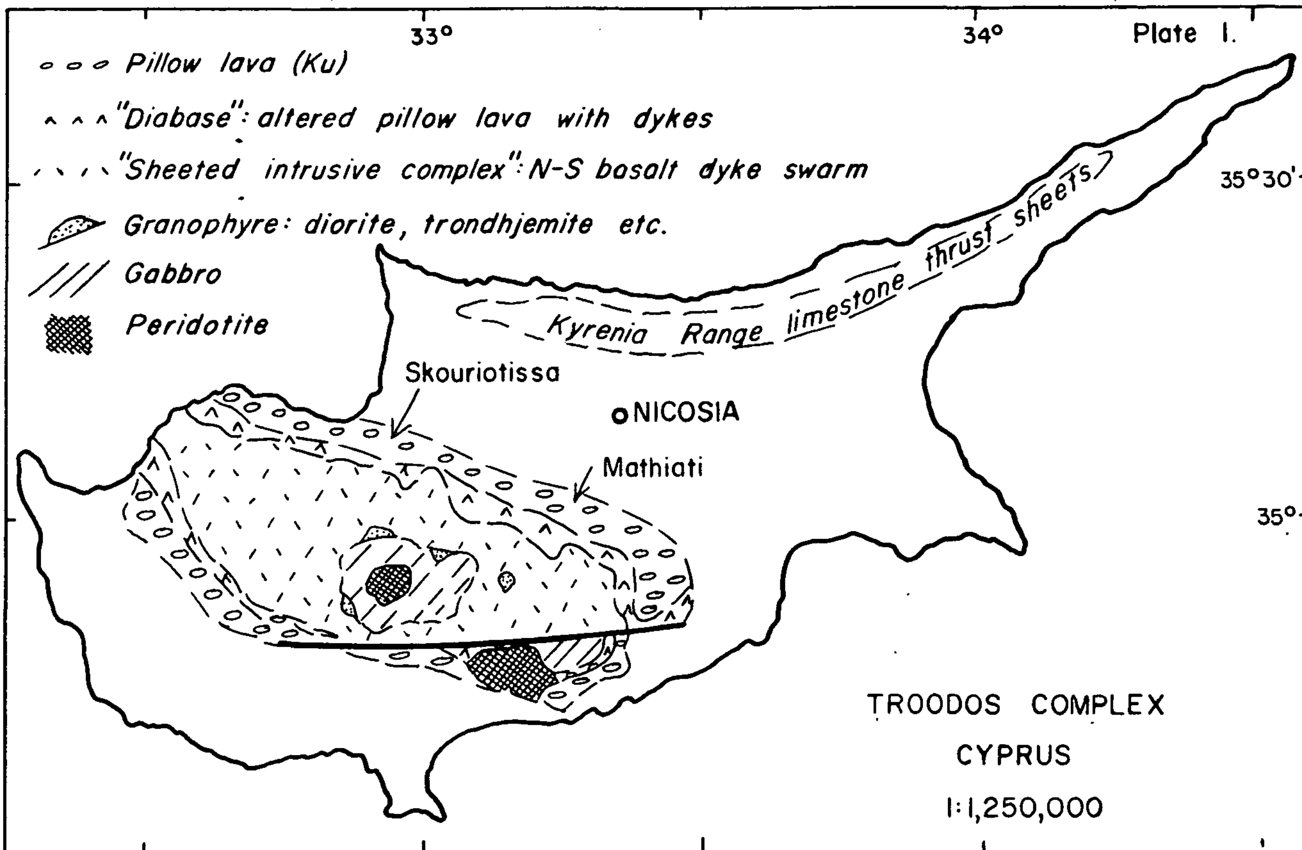
Cyprus is about 140 miles long east-west, and about 60 miles wide. The Kyrenia Range runs parallel to the north coast and is made up of sharp limestone ridges up to 3,000 feet high. The Troodos Mountains occupy the southern half of the island and have a high point, Mount Olympus, more than 6,000 feet above sea level. The capital of Cyprus, Nicosia, is on the Mesaoria, the plain which separates the two mountain ranges.

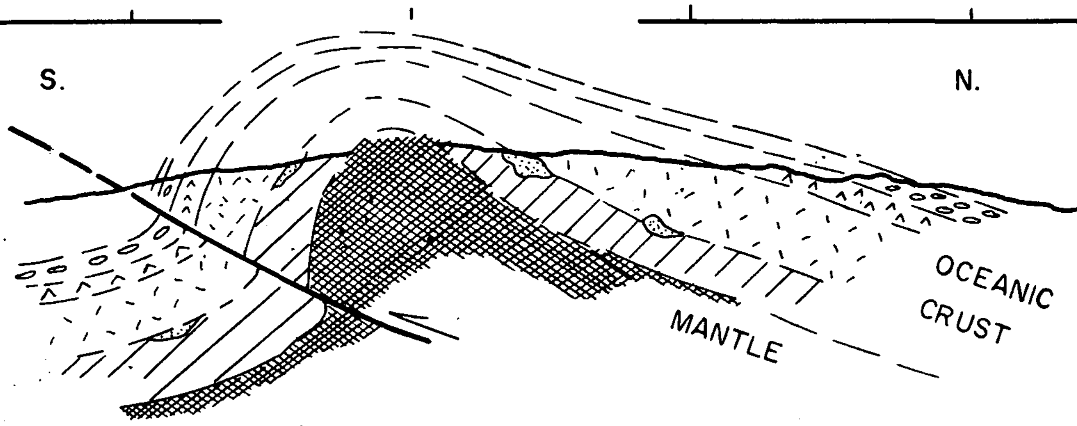
The sharp ridges of the Kyrenia Range are a series of thrust slices of Permo-Carboniferous and Upper Cretaceous limestone which dip steeply to the north. Thrusting took place in the Upper Cretaceous and Lower Miocene. Peter Knoup of the U.N. team showed me a remarkably detailed map of the range which he and another geologist had prepared for the groundwater project.

The Troodos mountain range is largely made up of the Troodos Igneous Complex: a series of layers folded into an asymmetric dome, steeper on the southern side and elongated east-west (see Plate 1). The layers are (from top to bottom):

Pillow Lavas, Upper & Lower	Basalt, relatively unaltered, with Upper Cretaceous radiolaria below and within U.P.L.
Basal Group	Pillow lavas of altered basalt with many dykes; some group these rocks with the Pillow Lavas, others with the Sheeted Intrusive Complex.
Sheeted Intrusive Complex ("diabase")	Basalt dyke swarm, N-S, steeply dipping; ratio of dyke rock to host rock (altered basalt) is about 10:1. Diabase here means altered basalt and dolerite.
Granophyre	Diorite, quartz diorite, trondhjemite, granodiorite; small irregular bodies.
Gabbro	Gabbro, olivine gabbro, norite.
Ultramafics.	Peridotite (mostly harzburgite), dunite, serpentinite.

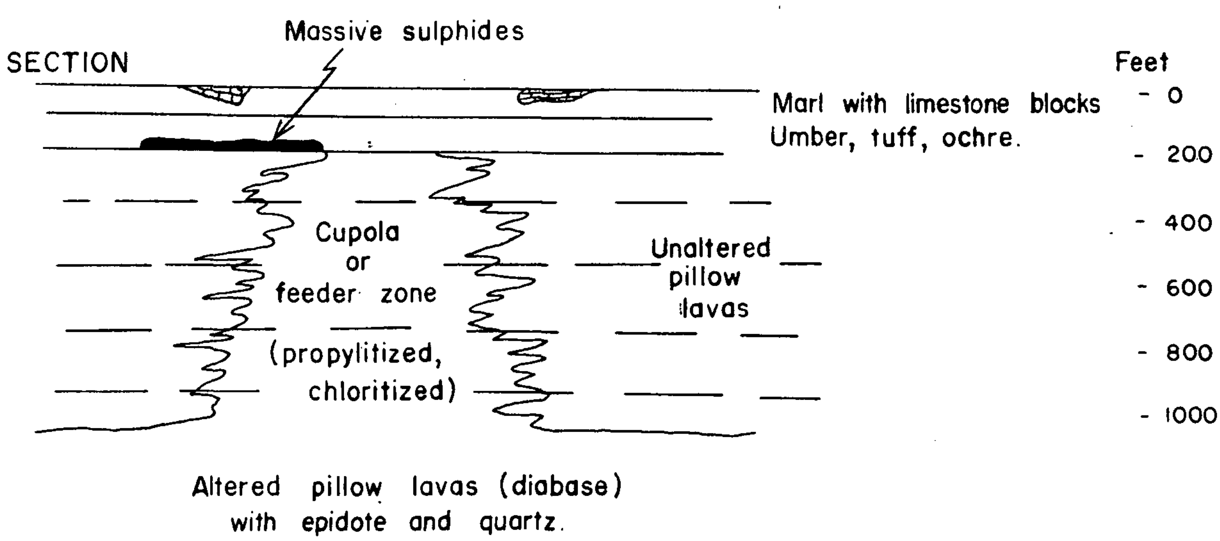
The peridotite is at the core of the complex and forms the highest point of the mountain range, Mount Olympus. It is mostly harzburgite and dunite with some wehrlite. Gabbro-peridotite contacts are mostly faulted but are in places transitional (e.g. near Kato Amandios and east of Prodhromous). Gabbro and peridotite show some layering but none with definite cumulus textures. Gabbro intrudes the overlying basaltic rocks and granophyre intrudes at the contact between gabbro and basalt.





Diagrammatic section shows possible structure — not to scale.

SKOURIOTISSA MINE — based on discussions with CMC staff



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The rock types and their textures and relationships are remarkably similar to those of the Papuan Ultramafic Belt. The only major differences are:

1) the relatively small outcrop of ultramafic rocks at Troodos,

2) Troodos gabbro does not intrude peridotite, and

3) the great volume of basalt as more-or-less parallel dykes in the Sheeted Intrusive Complex has no P.U.B. counterpart.

The small area of ultramafic outcrop is probably an accident of erosion, for the Bouguer gravity map (Gass and Masson-Smith, 1963; Gass, 1967) indicates a great mass of high density rock below the surface. The Sheeted Intrusive Complex must be explained by special local conditions, e.g. seafloor spreading (east-west).

Like the Papuan Ultramafic Belt the Troodos Complex is thought by most writers to be oceanic crust and upper mantle which has been thrust or buckled upwards. Gass (op.cit.)proposes that African sialic crust was thrust northwards under Cyprus during the Alpine orogeny. He proposed (Gass, 1967) that the gabbro and lavas were fluid in the Triassic but new palaeontological evidence (Pantazis, 1967, p. 134) indicates that overlying radiolarites are Upper Cretaceous and Gass (1968) proposes an Upper Cretaceous age for the gabbro and lavas. This age is confirmed for the pillow lavas by the discovery of Upper Cretaceous radiolaria at the interface between Upper and Lower Pillow Lavas (A. Panayiotou, pers. comm.). Thus the age of emplacement of the Complex may be Eocene, like the Papuan Ultramafic Belt. I collected samples of the Troodos granophyre for radiometric age determination in the hope that these might tell us more about the age of the complex. Similar rocks in the P.U.B. are Eocene (50-55 m.y.).

Most current theories on Troodos hold that there have been several distinct pulses of magmatic and tectonic activity. There may be good evidence to support these two or three-stage hypotheses, of which I am not aware. Bearing this in mind, I would suggest the alternative that the emplacement of the Complex by buckling or thrusting of oceanic "lithosphere", and the extrusion of the pillow lavas and the great dyke swarm, and the mobilization of gabbro and granophyre, were all penecontemporaneous in the Upper Cretaceous-Eocene.

Incidentally the concentric outcrop pattern of the various layers which comprise the Troodos Complex has misled Wyllie (1967, p.84) who classes Troodos with the Alaskan zoned ultramafic complexes when clearly the two are very different.

Mineralization in the Troodos Complex

Copper and iron pyrites were mined from Cyprus by the Romans, and before them the Greeks and Phoenicians; the English word copper is derived from the Greek name for the island, kypros. According to our guide almost all of the orebodies known today were known to the ancients, and traces of the old underground workings can be seen in the walls of many of the modern day open cuts.

Other minerals being mined on Cyprus include asbestos from the spectacular Amiandos quarry on the eastern flank of the Troodos peridotite, and chromite from underground workings north of Mount Olympus. Copper and nickel sulphides are associated in discontinuous veins in serpentinite in the south-eastern part of the Troodos Complex but are not in commercial quantity (Pantazis, 1967, p. 140).

The copper and iron pyrites ore bodies are restricted to the Upper and Lower Pillow Lavas and Basal Group and are thought to be exhalation products from the dying stages of volcanic activity. In support of this hypothesis the local geologists cite the present-day precipitation of pyrite in a fumarole on Nisoris (Nisyros?) Island near the island of Kos in the Aegaean (about 36°30'N, 27°E); trace element composition of pyrite from Nisyros Island and from Skouriotissa Mine (Cyprus) is similar (O. Kortan, pers. comm.).

The sulphides are commonly associated with lenses of iron- and manganese-rich claystone ("ochre" and "umber"). The exhalative hypothesis would maintain that these also are exhalative products and thus are indicators of favourable environment. There is also an epigenetic hydrothermal hypothesis which regards the ochre and umber purely as impervious caprock which trapped the ascending mineralized solutions. In either case ochre and umber are useful indicators in the search for sulphides.

I visited Skouriotissa Mine (Cyprus Mines Corporation) with George Constantinou of the Survey, and Al Johnson, a Canadian research student; we were cordially received by the engineer-in-charge, Oscar Kortan, and were given a thorough briefing on mine geology and on some results of the corporation's extensive drilling programme. We then spent several hours in Skouriotissa open cut where the ore-country rock relationships are beautifully exposed. In addition to this Mr. Panayiotou kindly took me on a tour of the North Mathiati Mine (Hellenic Mining Company) and the abandoned Sha and South Mathiati Mines.

Skouriotissa Mine

The Cyprus Mines Corporation was formed in 1916 to develop a copper and iron pyrites prospect at Skouriotissa, 28 miles west-south-west of Nicosia (Wilson and Ingham, 1959, p. 140). The corporation now operates three mines in this area.

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Skouriotissa Mine has been described by Wilson and Ingham and more recently in Geological Survey of Cyprus Bulletin 1, by Bear. The ore is massive sulphide averaging 2.25% Cu, 48% S and 43% Fe. It occurs as a lens at the interface between Upper Pillow Lavas and overlying sediments. The sediments are about 200 feet thick and consist of a top layer of marl overlying a sequence which includes umber, tuff and ochre. The marl contains irregular blocks of limestone. The umber is a dark brown cleaved manganiferous claystone about 20 feet thick; it is underlain by tuff which is in turn underlain by ochre: yellow brown ferruginous (goethitic) claystone. The ochre directly overlies the sulphides and is intercalated with them. The sediments appear gently synclinal but this may be due to collapse after removal of some sulphides by the ancients.

Mineralization is cut off by a fault, strike 300°, on the south side of the main pit; this face of the pit is a magnificent near-vertical exposure of pillow lavas. A westerly-dipping normal 360° fault separates the main pit from the smaller east pit.

Mr. Kortan explained that drilling indicates a "cupola" of alteration, which is probably a feeder zone below and to one side of the massive sulphides (see diagram); the cupola extends upwards from "Basal Group" altered basalts through unaltered pillow lavas; it measures about 300 feet in diameter and is about 1,000 feet deep. It is marked by propylitization and chloritization of the basalt, and differs from Basal Group basalt only in that it contains no epidote or quartz. Kortan suggests that the presence of epidote in the Basal Group is not a stratigraphic indicator (as the field geologists would have it) but is merely a function of depth at the time of hydrothermal alteration. He told us that cupolas are localized along preexisting east-west shears and that sulphides are associated with some and not others.

North Mathiati Mine

Hellenic Mining Company is producing iron pyrites from an open cut at the North Mathiati, about 14 miles south of Nicosia. The pit is cut into beautiful pillows of the Upper Pillow Lavas; mineralization is restricted to a fault-bounded block which strikes north-west across the pit. Silicified ochre which occurs with the ore in the centre of the pit reminded me of brown jasper-like rocks which occur on the Eia River on the Papua-New Guinea border.

Sha and South Mathiati Mines

These two mines are not being worked; both are rather small open cuts in which vestiges of ancient workings (oxidation around old shafts and drives, ancient timbers) can be seen. The Sha is in Lower Pillow Lavas, distinguished as such by the presence of green celadonite (cf. Cretaceous lavas at Morobe, N.G.) and opaline silica vesicle fillings.

The South Mathiati mineralization is in Basal Group faulted against Upper Pillow Lavas. Ancient tunnels exposed in the pit are no more than 3 feet high. Around the pit are extensive waste dumps.

Comparison of Troodos with the Papuan Ultramafic Belt

The Troodos Complex and Papuan Ultramafic Belt show a remarkable similarity in rock types, textures, and intrusive relationships, and this lends weight to the twin hypotheses that they are made up of oceanic mantle and crust. It is even possible that both were emplaced at about the same time.

Asbestos and chromite are being mined from the Troodos Complex; both have been found in the P.U.B. but not in commercial quantity. Copper and nickel sulphides which occur with serpentinite in subeconomic quantities in the south-eastern Troodos Complex are reminiscent of the small rich lenses of copper and nickel sulphides which have been found in gabbro-peridotite environment in the Keveri Valley, in the P.U.B. The most interesting comparison perhaps is the pyrite-chalcopyrite mineralization of the Troodos Upper and Lower Pillow Lavas. Mineralization of this type has been found in the Bowutu Mountains from near Kui (7°30'S) to the Waria River (8°S) and at scattered points to the south. In the arid environment of Cyprus the sulphides are marked by prominent gossans; similar concentrations of sulphides if present in Papua-New Guinea would be concealed by a cover of soil and rain forest and would be that much more difficult to find.

Conclusions

The Cretaceous pillow lavas associated with the Papuan Ultramafic Belt may contain economic pyrite - chalcopyrite mineralization of the type seen in the Upper and Lower Pillow Lavas of the Troodos Complex. We should look for umber and ochre occurring with the ubiquitous pillow lavas of eastern Papua, and elsewhere in New Guinea, for these may be indicators of nearby sulphide mineralization.

ULTRAMAFICS OF THE MASSIF CENTRAL, FRANCE (29 JULY - 2 AUGUST)

Leader: Prof. F.H. Forestier (Univ. de Nantes)

Assistant: M. Lanier

Participants: Prof. & Mrs Van der Kaaden (Heidelberg), F. Wicks (Oxford), H. Schorscher (Heidelberg), ourselves.

Narrative

From Cyprus we flew to Zurich for a few days rest in the Swiss Alps, then to Geneva on the morning of 29 July. In Geneva we rented a small car from Hertz and drove westward across the border and through the Jura Mountains into France. We reached our rendezvous, Clermont-Ferrand, in the early evening, and next day presented ourselves at the university where we met some of the geology graduate students. All of the students had the same problem: where to find work. They were interested to hear of opportunities in Australia and I gave them some addresses. They told us that their university had escaped most of the disruption of the May student uprising, perhaps because it is quite a new school with good facilities.

Later in the day we met Professor Forestier and Mr Lanier of the University of Nantes. Professor Forestier has spent ten years in a detailed study of the headwaters region of the Allier River south of Clermont-Ferrand (Forestier, 1963), and in the following days he was to show us something of the ultramafic rocks in this area (Forestier, 1964).

The excursion started on the afternoon of the 29th with a brief account of the regional geology, then we set out for Brioude, visiting several points of interest on the way. Over the next two days we continued our tour of the Upper Allier region, spending the nights of 30th and 31st July and 1st August at beautiful Le Puy on the Loire. On 2nd August we drove eastward to Grenoble then through the Alps as far as Sestriere in Italy. At Sestriere we were to begin the second part of our European tour: a study of the Alpine ophiolites and ultramafics.

The tour party which gathered at Clermont-Ferrand included Prof. & Mrs Van der Kaaden of the University of Heidelberg, a student from Heidelberg, H. Schorscher, and a student from Oxford, Canadian Fred Wicks. The Van der Kaadens had spent most of the last 17 years in Turkey and he had much interesting information about the ultramafics (and archaeology) of that country. Mr. Wicks has been making a study of serpentine minerals combining microscope and electron probe, and believes that he has found reliable criteria for distinguishing the different serpentine minerals optically.

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Outline geology of the Massif Central

The Massif Central is a block of crystalline rock in southern central France surrounded by Mesozoic sediments on all sides. The northern part of the Massif, north of a line between Limosge and Lyon, is Precambrian; the southern part is Devonian to Middle Carboniferous (300-275 m.y.). The Hercynian orogeny has affected the entire Massif and the Precambrian parts have thus been subject to two metamorphic events. The Hercynian orogeny was in two stages: folding, metamorphism and granitization in Middle Carboniferous, followed later by strike-slip faulting.

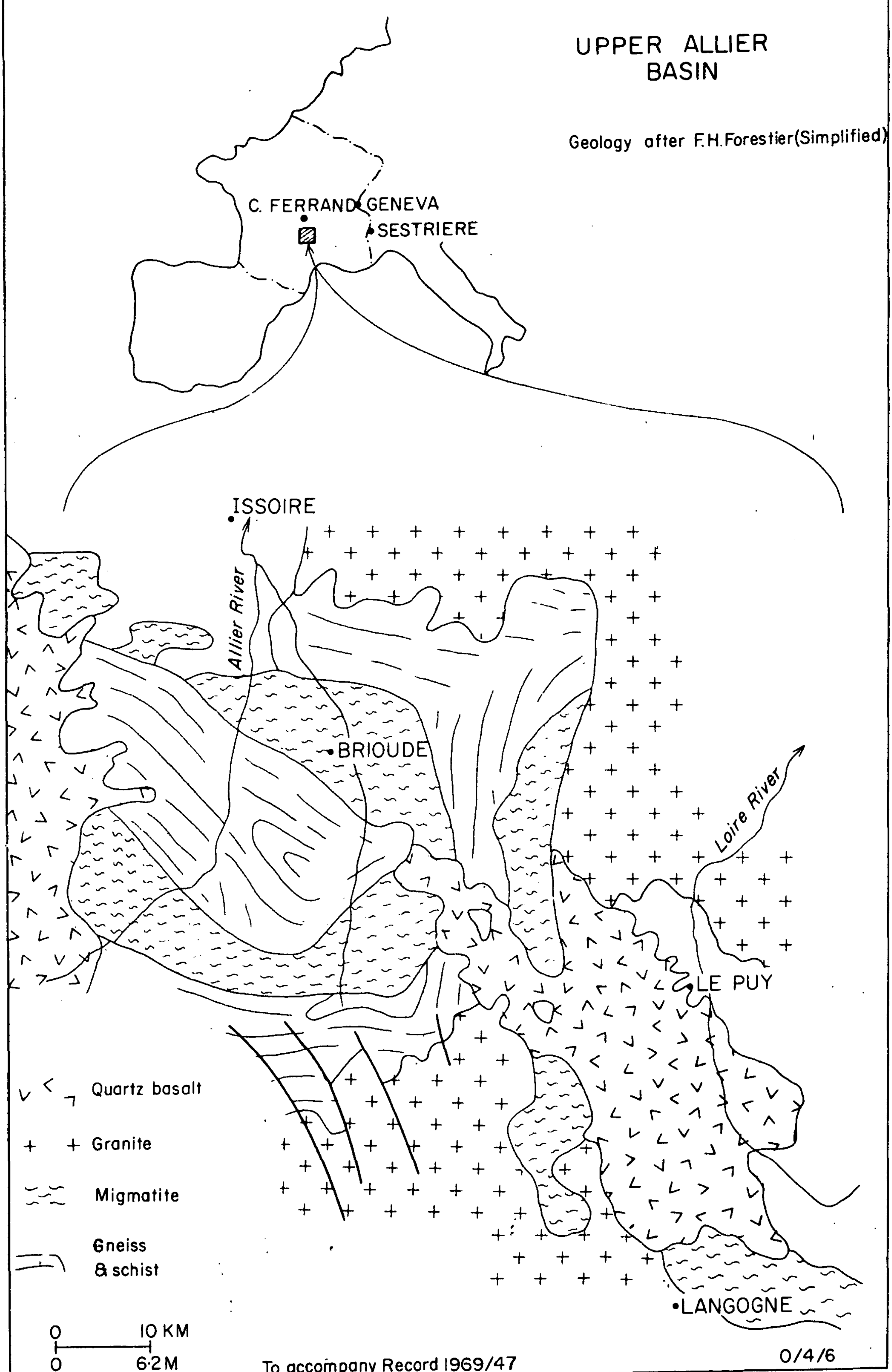
The Alpine orogeny brought renewed faulting, followed by vulcanism and the development of north-south grabens in the Oligocene to Sub-Recent.

Geology of the Upper Allier Basin

The Upper Allier basin is in the south-eastern central part of the Massif Central at about 45°N, 4°E. The area mapped by Professor Forestier covers about 10,000 km^2 and includes the towns of Le Puy in the east, Issoire in the north, Brioude in the central north, and Langogne in the south. It is a hilly area with peaks up to 1200 metres above sea level and is only about 50 percent cultivated.

The area is bounded to north, south, and east by the Hercynian (275-300 m.y.) granites of Margeride, Velay, and Livradois. To the west it is bounded by a cover of Pliocene and Quaternary basalts. The central part is made up of a folded sequence of schist, gneiss, and migmatite distributed as follows. In the central west is the Massiac synclinorium which trends NW - SE and consists largely of sillimanite-bearing gneiss. This is surrounded by an anticlinal corona of coarse-grained anatexites which are biotite and cordierite-bearing. This corona is bounded on three sides (SW, SE, NE) by an upper group of crystalline schists which are folded into the Desge-Senouire-Doulon (D-S-D) synclinorium. This upper group of schists has been subject to a second (retrograde) metamorphism. To the east the schists give way to augen gneiss and migmatite, and this same gneiss and migmatite is seen in the core of the D-S-D synclinorium to the south. Peridotite occurs at various levels in the metamorphic sequence as bodies which range in size from fist-size up to 1 km. across.

Plate 2



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Geological history of the Upper Allier Basin

Professor Forestier (1963, pp.247-8), suggests that the metamorphics are derived from a sequence of geosynclinal sediments which include acid and basic volcanics, and that the peridotite originated as intrusions into basic volcanics. I think he now believes that the peridotite inclusions are brought into the sequence by faulting from depth (see later). Previous workers in other parts of France had tried to explain the peridotite inclusions as metasomatized pieces of reef limestone; this hypothesis cannot be supported in this area.

The sediments and volcanics were subjected to two cycles of metamorphism and migmatization, one in the late Precambrian or Ordovician - Silurian (Caledonian), and the other in the late Devonian - early Carboniferous (Hercynian). The granites which surround the metamorphics on three sides were generated in the Hercynian orogeny (op.cit.)tables p.260).

Catalogue of peridotite inclusions

Professor Forestier has set himself the task of documenting all of the occurrences of serpentinized peridotite in France. He provided us with the volume which covers the Upper Allier basin (Forestier, 1964). It is a loose-leaf folder of 292 pages; each peridotite locality is described in one or more sheets of paper and has an index number which appears in the accompanying geological map. The descriptions follow a set pattern: name; locality; size; outcrop quality; country rock; type of ultramafic rock; degree and type of serpentinization; basic differentiates associated; degree of weathering; alteration products; nature of contacts; any acid veining; contact phenomena for acid veins; metasomatic alteration of the ultramafic body; bibliography; when visited. We inspected many of these localities in the three days of our tour, each locality showing some different aspect of mode of occurrence or mineralogy. I will try to summarize what we saw.

Peridotites of the Upper Allier Basin

The largest body of peridotite is a slab 1 km. long and less than 100 metres thick which is situated in the upper group of metamorphics at a point about 35 km west of Le Puy. It is concordant within the surrounding gneiss and dips at 45° NW. The rock type is moderately serpentinized harzburgite.

The smallest bodies of peridotite that we saw are fist-sized rounded inclusions in gneiss and anatexite. The inclusions in acid gneiss or "leptinite" have well marked reaction rims which are zoned with fibrous amphibole on the inside and brown vermiculite on the outside. Inclusions in anatexite have much thinner reaction rims.

We saw the same type of reaction effects at a number of localities, and at some we found a corresponding desilicification of the acid rocks. Thus a granite vein intruding the largest body of peridotite is altered from normal two-mica granite at the centre to a white granite devoid of quartz and poor in mica at the margins. In other cases more severe reaction has converted granite veins to corundum plagioclasite consisting of albite/oligoclase, corundum, and biotite.

Some of the medium-size peridotite bodies that we visited have been quarried for road aggregate and in one case for asbestos. Most of these bodies show some alteration at the contacts and especially where the enclosing rock is acid gneiss or granite. In some cases the alteration follows sets of rectangular joints and small rounded cores of unaltered peridotite are preserved between the joints. Typically the alteration zones around these cores are as follows:

(1) serpentinized peridotite (2) gedrite (3) vermiculite (brown) with actinolite (green) (4) vermiculite.

Three unusual rocks are associated with the ultramafics at different localities. These are: (1) kyanite-garnet rock, (2) diopside-grossularite rock, and (3) a corundum amphibolite. The association of peridotite with these unusual rock-types might be evidence that the peridotites are faulted up from depth rather than intruded as magma.

THE OPHIOLITE PROBLEM

Our examination of ultramafic rocks in the Alps brought us into contact with the rocks of the ophiolite suite. I have never clearly understood the meaning and applications of the term ophiolite and so undertook a brief programme of research into English, French, and German literature. The results of this research are presented here with the hope that they may be of some use to others. In particular I consulted Steinmann (1906, 1927), Trümpy (1960), Vuagnat (1963) and Aubouin (1965). Other useful references are Burri and Niggli (1945), Hess (1955), Gansser (1959) and Thayer (1967).

Ophiolite is a Mediterranean and particularly Alpine term for basic and ultrabasic, plutonic hypabyssal and volcanic rocks, altered in varying degree. Synonyms are greenstone, roches vertes, and pietri verdi. According to Steinmann (1927) typical unmetamorphosed ophiolites consist of serpentine overlain by gabbro which is in turn overlain by diabase-spilite. Aubouin (1965) defines the ophiolite suite in more detail:

(1) Fine-grained rocks: basalts, spilites and pillow lavas

(2) Medium-grained rocks: dolerites

(3) Coarse-grained rocks: peridotites, pyroxenites, pyroxeno-peridotites (often altered to serpentinite), gabbros, diorites, and quartz diorites.

To these rock types Trümpy (1960) adds tuff, and various metamorphic derivatives such as prasinite (chloritic basic schist) ovardite (calcic basic schist) and other "greenstones".

Aubouin agrees with Steinmann that the rocks are normally arranged with peridotite or serpentinite at the base and basalt or diabase at the top, but goes on to say that the basalt and dolerite form a shell which completely encloses the coarse-grained rocks. This is an essential point in his theory of origin (see later). Whereas Steinmann (op.cit.) and Vuagnat (1963) describe gabbro and diabase intruding peridotite, and diabase intruding gabbro, Aubouin maintains that there are no clear-cut boundaries between the different rock types "for they merge gradually into one another, both texturally and in mineral composition". This too is an essential point in his theory of origin. Aubouin also takes particular note of the diorite and/or quartz diorite which occur at the gabbro-dolerite interface, a feature not mentioned by the other writers.

Steinmann (1906) drew attention to the fact that the ophiolites are commonly associated with deepwater sediments such as radiolarian chert, fine-grained limestone, and argillite: the association serpentine-spilite-chert came to be known as Steinmann's Trinity (e.g. see Bailey and McCallien, 1953; Hess, 1955). As noted above, Steinmann (1927) later pointed out that gabbro is an essential part of the ophiolite-chert association, but this fact has been commonly overlooked (see discussion by Thayer, 1967, p.222). Steinmann (op.cit.) proposed that rocks of the ophiolite suite are intruded as a basic laccolith into the deepwater sediments but this hypothesis has lost favour because it has been widely recognized that pillow texture in the spilites indicates extrusion on the sea floor.

In the western Alps the ophiolites, with or without associated chert, are typically emplaced in Schistes lustrés: metamorphosed Mesozoic eugeosynclinal sediments typified by calcareous sericite schist, non-calcareous slate and schist, micaceous marble and micaceous quartzite (Trümpy, 1960, pp. 860-861). Metamorphism probably took place during the Alpine orogeny in Oligocene and early Miocene time (op.cit.). Contacts between Schistes lustrés and ophiolite are typically faulted.

In his review of the ophiolites of the western Alps, Grisons, and the Appenines, Vuagnat (1963) notes that (a) peridotites are mostly serpentinized, gabbros saussuritized, and basalts chloritized and commonly spilitic, (b) the gabbros typically show marked variations in grainsize which might indicate a high volatile content, and (c) there is no thermal metamorphism at the ophiolite contacts.

Hypotheses of origin of ophiolites

Vuagnat (op.cit.) places the hypotheses in four categories:-

1. Transformist hypothesis. The ultramafic part of the ophiolite group was formed by metasomatic alteration of sediments. This hypothesis has few supporters nowadays; it is reviewed by Sorensen (1967).

2. Pure volcanic hypothesis. Peridotite magma was extruded on the deep sea floor, e.g. Bailey and McCallien (1953) and Rittmann (1958). This too is not a popular hypothesis today.

3. Vulcano-plutonic hypothesis. This is the hypothesis favoured by Aubouin (op.cit.), Gansser (op.cit.) and by others who have worked in Greece, Turkey and Syria, e.g. Brunn (1956, 1960) and Dubertret (1953). We must envisage a massive lava flow, between one and five km. thick, extruded onto the ocean floor. The exterior chills to form a crust or shell of pillow lavas and massive dolerite; the interior cools more slowly and differentiates into peridotite, gabbro, and a little diorite or quartz diorite.

Vuagnat (op.cit) points out that in the typical ophiolite massif the proportion of peridotite to gabbro is too high to be explained by differention from a basaltic melt. Whereas the two should be in the ratio of 1:5 or 1:10 they are usually 1:1 or higher. For instance in the western Alps the ratio of serpentinite outcrop to all ophiolite outcrop is 5:7. Also if the ultramafics have differentiated from a basaltic melt there should be a comparable fraction of rocks more acid than basalt. Brunn (op.cit.) suggests that great quantities of Si, Al, K, Na, etc. have escaped into the ocean. If this is the case it has happened without leaving any record, such as metasomatism of the pillow lavas or development of unusual rock types nearby.

Apart from these arguments Vuagnat balks at the size of the flow. Dubertret (1953) met this problem by suggesting that magma is introduced into and expands the shell of pillow lavas in a series of successive injections.

4. Subcrustal hypothesis. Most geologists now believe that the Alpine peridotites are faulted segments of upper mantle, and that the associated basalt and gabbro developed by partial melting of mantle rocks perhaps during the same tectonic event which brought the mantle segments to the surface. An alternative (suggested to me by E.D. Jackson) is that the basalt and gabbro were generated from mantle rocks at a locus of seafloor spreading, comparable to one of the present-day mid-ocean ridges.

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Vuagnat points out that the idea that the Alpine peridotites are tectonic lenses or slices brought from depth during orogenesis was proposed by Hiessleitner (1952) from his work in the eastern Alps, Balkans, and Turkey. The idea that these lenses originate in the upper mantle was developed by Hess (1955) and de Roever (1957).

Ophiolite and the two types of Alpine peridotite

Alpine peridotites are fault-bounded ultramafic bodies typically located in folded eugeosynclinal sediments in the orogenic belts. Many are associated with gabbro and/or spilite and thus are integral parts of the ophiolite suite.

Typical Alpine peridotite is a mixture of olivine, enstatite, and chromite, as dunite, harzburgite and pyroxenite; these rocks are predominantly magnesia and silica with very little alumina or lime. Another type of Alpine peridotite is seen in the innermost western Alps, at Davos in the Graubünden Alps, and at Lherz in the Pyrenees. It consists of olivine, aluminous enstatite, aluminous diopside, and spinel, and the typical rock type is lherzolite. Chemically the second type differs from the typical alpine peridotite in containing appreciable Al_2O_3, CaO, and Na_2O.

The lherzolite type of Alpine peridotite may be primary mantle (e.g. MacGregor, 1967) and the harzburgite type may be secondary or refractory mantle, a residuum from the fractionation of basalt magma from primary mantle.

Ophiolites and the Papuan Ultramafic Belt

The Papuan Ultramafic Belt is apparently a typical ophiolite body of the eastern Mediterranean type. Basal peridotite is overlain by gabbro which is in turn overlain by dolerite and basalt, and diorite and quartz diorite intrude at the gabbro-dolerite interface. Contacts between the different rock types are generally intrusive but in some places appear to be gradational e.g. in parts of the Musa area and of the Ajura Kujara Range and Bowutu Mountains there are apparent transitions from peridotite to gabbro, and from gabbro to dolerite and basalt. Intrusive relationships are as follows:

gabbro and diorite intrude peridotite
gabbro and diorite intrude dolerite and basalt
basalt dykes intrude gabbro

The subcrustal hypothesis of origin best fits the Papuan Ultramafic Belt, but we should note that in places there are pillow lavas apparently below the peridotite, i.e. on the south-western side of the bounding fault. According to the vulcano-plutonic hypothesis these would be remnants of the lower part of the basalt shell; according to the subcrustal hypothesis they can be explained as segments of oceanic crust caught in the zone of thrust-faulting.

According to Aubouin (op.cit.) ophiolites are normally emplaced in eugeosynclinal environment from a source on the flank of the geanticlinal ridge which separates eu- from miogeosyncline. This is not so in the case of the P.U.B. which appears to have been emplaced by thrusting from the oceanic side of the eugeosyncline.

According to the Subcrustal hypothesis any ophiolite body has three "ages": 1) age of crystallization of earth's mantle, 2) age of generation, mobilization and crystallization of basaltic magma, and 3) age of faulting which brings the mantle rocks to the earth's surface. The first age should be the same for all ophiolites and is presumably around 4000 m.y. The second age, where known, is surprisingly uniform and varies from Middle or Upper Jurassic to Upper Cretaceous, for the Mediterranean and many other ophiolites.

In the case of the Papuan Ultramafic Belt it is probably Middle or Upper Cretaceous (based on one radiometric age of 116 m.y. and some indirect microfossil evidence) with an Eocene quartz diorite phase (based on several radiometric ages of 50-55 m.y.). In the Alps the third age is probably Eocene, Oligocene or Lower Miocene, i.e. during the Alpine orogeny. Emplacement was probably related to the Alpine metamorphism which Trümpy (op.cit.) restricts to Oligocene and possibly Lower Miocene. I have suggested (Davies, 1968) that the third age of the P.U.B. is Eocene because emplacement might conceivably be related to the generation of the quartz diorite magma mentioned above. It is also possible that the third age of the P.U.B. is Oligocene or Lower Miocene. Similarly the ultramafics of New Caledonia may have been emplaced in the Oligocene or Lower Miocene, for metamorphic minerals which probably developed at the time of emplacement give radiometric ages of 21 - 38 m.y. (Coleman, 1967).

Use of the term "ophiolite"

From the foregoing discussion it seems that the ophiolite suite is a worldwide phenomenon and that the Papuan Ultramafic Belt is a fairly typical example. In fact if the term ophiolite were in common use amongst English-speaking geologists the Ultramafic Belt might be more aptly called the Papuan Ophiolite Belt. However my impression is that confusion still exists among English-speaking (and perhaps among continental) geologists as to the exact meaning of the term, and as long as this is the case we would do better not to use it.

For this reason I would suggest that Thompson and Fisher's (1966) use of the term Ophiolite Province for eastern Papua, though a convenient shorthand, should not be perpetuated in subsequent publications.

Apart from the argument as to whether the term is understood by English-speaking geologists, it is likely that most European geologists associate "ophiolite" with relatively small faulted blocks like that at Mont-Genevre, or with larger layered masses like those of Greece and Turkey (and the P.U.B.). I doubt that they would extend the term to include the enormous volume of pillow lavas with only very minor intrusives, which make up the easternmost Papuan mainland, no matter how logical this might seem to us. Instead of an Ophiolite Province in eastern Papua I suggest we use terms like (a) peridotite - gabbro-basalt province and (b) basalt province.

Use of the term "alpine peridotite"

Ultramafic rocks have been commonly subdivided into (a) those associated with layered intrusions such as the Bushveld and Stillwater complexes, and (b) the alpine peridotites; a third group, (c) the Alaskan zoned ultramafic bodies, has been defined more recently. The term alpine peridotite or serpentinite was originally applied to fault-bounded ultramafic bodies located in folded geosynclinal sediments in the orogenic belts. Usage of the term has been widened to include any ultramafic body other than those in types (a) and (c). Thus the group includes bodies ranging from fault slivers of serpentinite to great masses of unaltered peridotite; most of these occur in orogenic belts, but not always associated with folded geosynclinal sediments, and, as noted in the discussion of ophiolites, many are intimately associated with gabbro, quartz diorite, and basalt. Furthermore the peridotites of the Alps include both the primary mantle (aluminous lherzolite or pyrolite) and refractory mantle (dunite-harzburgite) types. Thus the term alpine peridotite has lost any precise meaning that it once had and should perhaps be redefined as one member of a larger group of what might be called nonmagmatic or mantle peridotites.

MONT-GENEVRE OPHIOLITE MASSIF: AUG. 3-4

Guide: Professor Marc Vuagnat of Geneva

Participants: T.P. Thayer (U.S.G.S., Washington, D.C.), E.D. Jackson (U.S.G.S. Menlo Park, California), Professor Van der Kaaden (University of Heidelberg), A. Nicolas and Professor F.H. Forestier (University of Nantes), Professor M. Galli, and G. Piccardo and A. Bezzi (University of Genoa), Professor D.S. Coombs (University of Otago), H. Helmers (University of Amsterdam), D. Steen (University of Geneva), H. Schorscher (University of Heidelberg), and ourselves.

Narrative:

We met at the Albergo Miramonti, Sestriere, in the Italian Alps west of Turin, on the afternoon of August 2nd. We had enjoyed an exhilarating drive from LePuy by way of Grenoble and the Mont-Genevre pass through the Alps. Sestriere is a ski resort more or less deserted in the summer, except on weekends when the crowds emerge from Turin to picnic in the mountain air and to gather the plant from which the local liquor is made.

On August 3 and 4 we were guided by Professor Marc Vuagnat of Geneva in an examination of the Mont-Genevre ophiolite massif. On the 5th Professor Vuagnat returned to Geneva and we moved north-east to Germagnano, a small town on the Lanzo River north-west of Turin, to begin the next stage of our tour.

Our group included Tom Thayer of U.S.G.S. who is known for his work on alpine ultramafics and chromite deposits. Tom and Adolphe Nicolas of Nantes are the original organizers of the trip. We also met Dale Jackson of U.S.G.S. who is known for his study of the Stillwater Complex, Montana, and is currently working on inclusions in Hawaiian basalts. Doug Coombs from the University of Otage was an unexpected and welcome addition to the party - he was on sabbatical in Geneva - and in addition we found Professor Galli and Messrs Bezzi and Piccardo from Genoa who were to prove invaluable as guides and organizers in the succeeding days. The remainder of the group was made up of an ophiolite researcher from Amsterdam, Mr. Helmers, another student from Geneva, Mr. Steen, and the members of the party from Le Puy.

OPHIOLITE AND ALPINE PERIDOTITE LOCALITIES

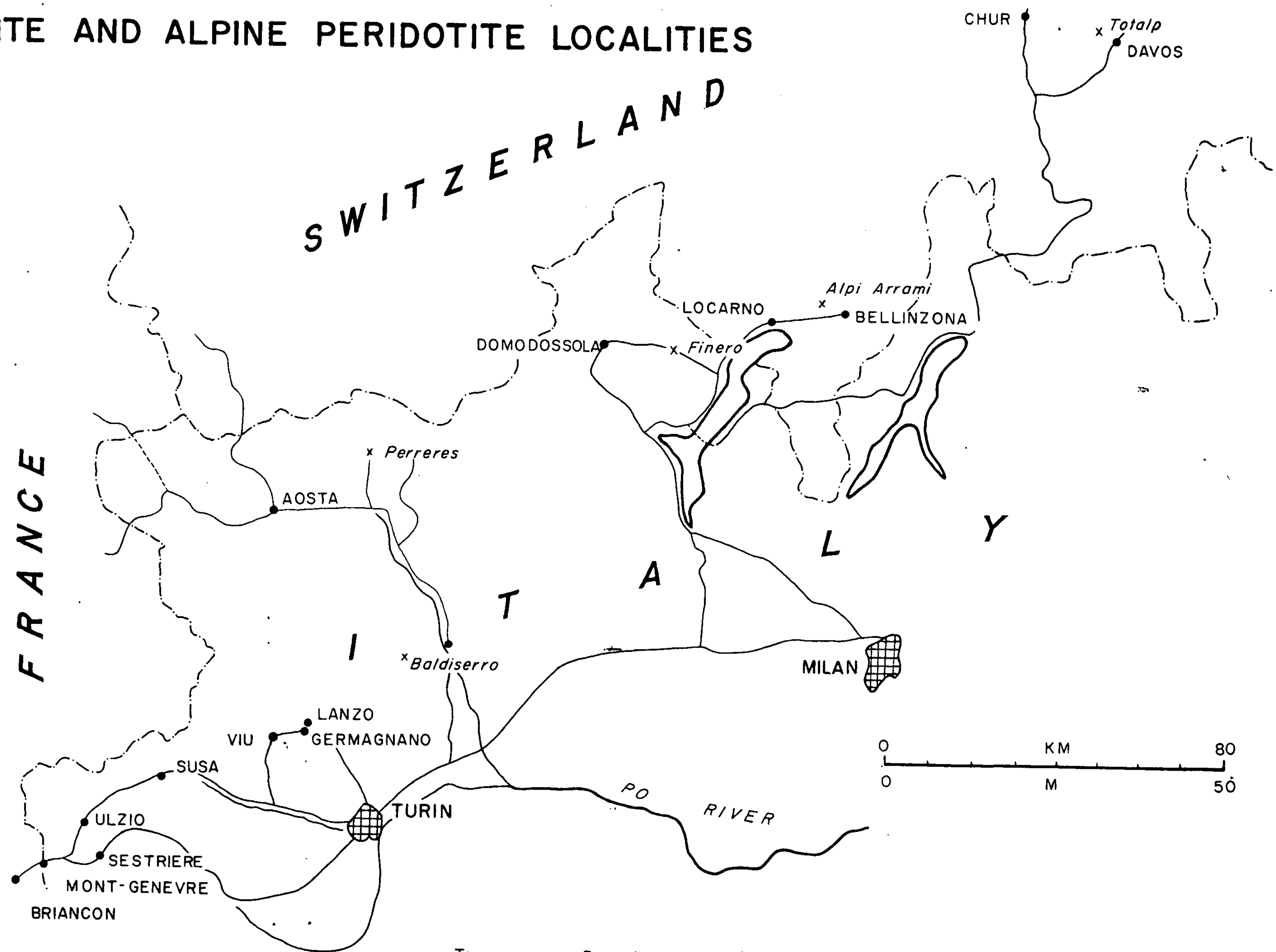

PLATE 3

To accompany Record 1969/47

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Mont-Genevre Geology

The geology of the Mont - Genevre massif is summarized in a field trip report (Vuagnat et al, 1966); in addition we received duplicated notes, a map, and reprints dealing with specific aspects. The massif lies due south of the town of Mont - Genevre and straddles the French-Italian border; highest point is La Chenaillet, 2749 m. The massif consists of serpentinite, gabbro, pillow lavas, and a little syenite. Professor Vuagnat pointed out that it is less metamorphosed than the typical Alpine ophiolite: possibly because it originated at a higher less-metamorphosed level of the Alps and has been protected from erosion by down-faulting. It is underlain by prepiemontaise flysch and calcareous sediments and may be conformably overlain by piemontais schistes lustrés (calcareous sericitic schist, etc.). Age of the ophiolite massif is not known; the K-Ar age of augite from a basalt dyke is Middle Cretaceous, 100 m.y. (Vuagnat et al, 1966).

Relationships between the different rock types of the massif are not obvious in the field except that basalt dykes intrude gabbro, and acid solutions which may be related to the syenite appear to have affected the gabbro. Gabbro is generally coarse-grained but grain-size is variable; it includes mafic schlieren and feldspathic segregations.

Ophispherite is the name which Professor Vuagnat (1953, 1967a) has coined for rodingitized sub-spherical inclusions in the serpentinite north-east of Chenaillet. The only other known occurrence is at Col des Gets (Jaffé, 1955). The cores of the spheres are whitish, have relict diabase (basalt) texture, and consist of chlorite and augite. The rims are dark and consist of aluminous chlorite and a little magnetite. The ophispherites probably are basalt dykes which have been broken up and the fragments rounded by attrition during shearing of the host serpentinite.

The pillow lavas are beautifully exposed on the slopes of Chenaillet and to the north-east; most are normal basalt but some are spilitic. Professor Vuagnat pointed out that the pillows are connected by lava tubes which swell and bifurcate if traced in the bedding plane; thus it is possible to determine in which direction the lava flowed.

Much of the pillow lava is variolitic; the varioles are white ovoids and are commonly concentrated towards the pillow margins. Prof. Vuagnat explained that the varioles are centres of crystallization in which clinopyroxene and plagioclase have developed as fine laths. The remainder of the rock is dark coloured and consists of chlorite after glass.

Hyaloclastite (palagonite tuff) is another unusual rock type on Le Chenaillet; it occurs intercalated in the pillow lavas. Vuagnat and Pusztaszeri (1965) propose that it forms by the explosion of pillows. The surfaces which we saw contain angular fragments of former glass and a few fragments of pillows. Overall chemical composition is that of a spilitic basalt with 4.64% Na_2O, 5.39% CaO, and 2.38% TiO_2 (ibid).

Pillow breccia (Vuagnat, 1967b) at Lago Nero, south-east of Chenaillet, consists of angular pieces of chloritized basalt, some with varioles. Professor Vuagnat suggests that the breccia formed as the lava advanced by the breaking of the outer skin. Also at Lago Nero we saw rodingitized gabbro pegmatite in serpentinite, and a possibly conformable contact between pillow lavas and overlying Schistes lustrés.

Metamorphosed pillow lavas: Between Mont-Genevre and Sestriere Professor Vuagnat showed us basic schists in which former pillows could be recognized by the trace of the variolitic pillow rims, now stretched into ellipsoids. At Ulzio, five miles to the north, we saw glaucophane schist in which pillow and pillow breccia textures are preserved (Gay, 1966).

Ophicalcite is serpentinized peridotite which has been permeated by limey solutions; we visited a quarry at Cesana where slabs are cut to be used as "marble" facing for buildings, etc.

Mont-Genevre and Papua - New Guinea

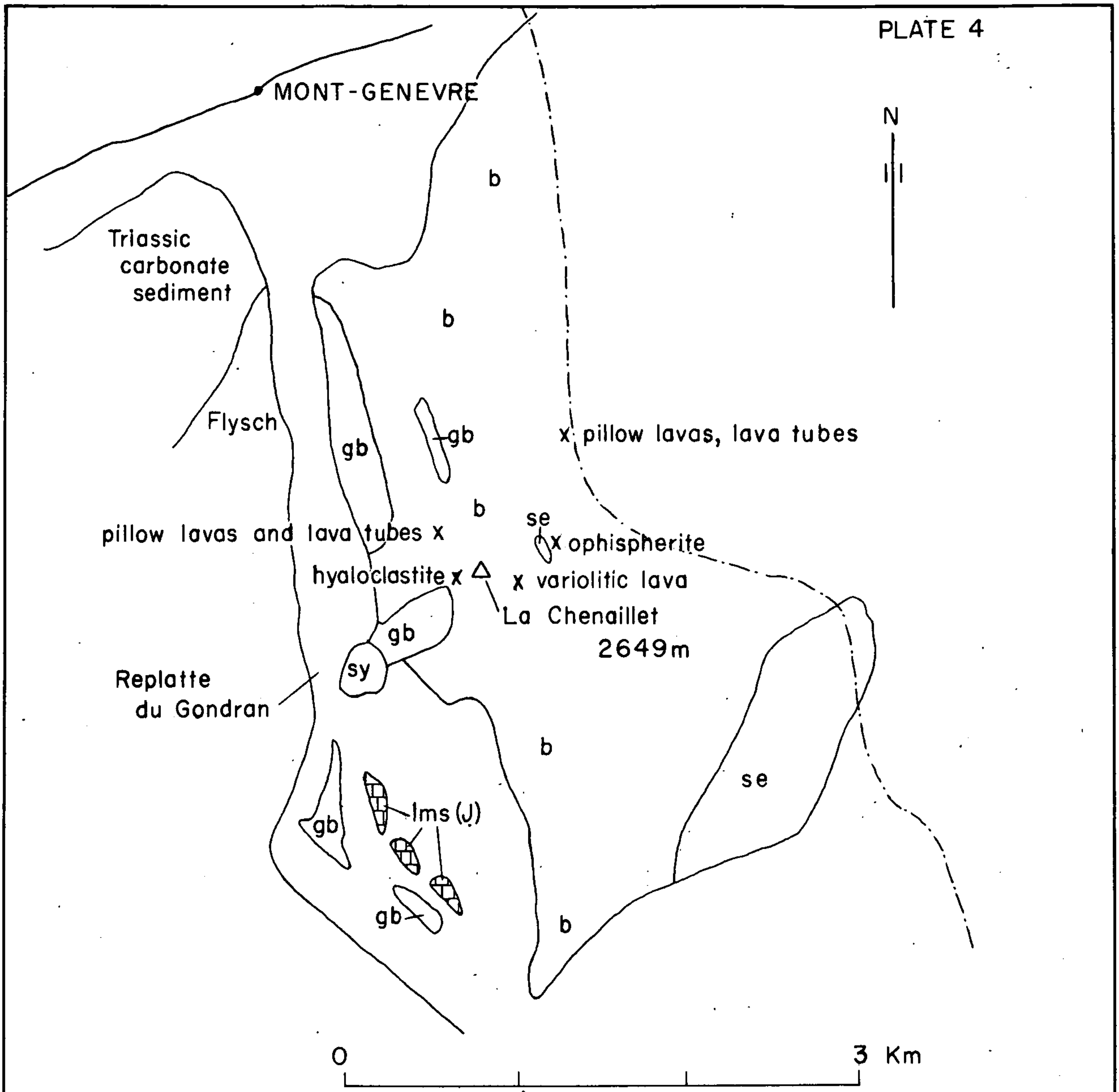
In view of the great extent and, in places, excellent exposures of pillow lavas in Papua-New Guinea, I would think that a closer examination of these rocks might produce information of world-wide interest, just as Professor Vuagnat's study of the Mont-Genevre pillows has done.

As far as I know lava tubes have not been recorded from Papua-New Guinea, but this is probably simply a reflection of the lack of detailed mapping. Similarly variolitic pillows, pillow breccia and hyaloclastite have not been recorded to the best of my knowledge.

The varioles at Mont-Genevre put me in mind of the mysterious ovoids, up to the size of a golf ball, which we have found in the Bailebo and Bonua Rivers. These ovoids are in a pale grey hard dense rock which I called, in the field, a thermally metamorphosed limestone. I would suggest now that it is a variolitic glassy lava; perhaps my co-workers have already determined this from the thin sections.

Another lesson for me at Mont-Genevre was that rocks which to the uninitiated would seem most unsuitable, such as calcified serpentinite, may in fact be valuable facing stones. If Italian marble can be brought to Australia for the National Library building it is not beyond the bounds of possibility that Papua-New Guinea could be a source of ornamental stone, and we should bear this in mind in future fieldwork.

PLATE 4



sy Syenite
b Basalt
gb Gabbro
se Serpentinite
lms(J) Limestone Jurassic

MONT-GENEVRE OPHIOLITE

based on a sketch map provided by Prof. M. Vuagnat

To accompany Record 1969/47

0/4/8

LHERZOLITE AND GARNET PERIDOTITE: LANZO, BALDISSERO, FINERO, AND ALPI ARRAMI

August 5-7, 10-12

Guide: A. Nicolas

Participants: Thayer, Jackson, Wicks, Galli, Piccardo, Bezzi, Coombs, Van der Kaaden and Schorscher (until August 10), and ourselves.

Narrative

Monday August 5th we left Sestriere and drove north. After our first stop at Ulzio in the Susa valley we said goodbye to Professors Vuagnat and Forestier. At this point Dr. Nicolas, Maitre Assistant to Forestier at Nantes, and formerly of Grenoble, became our tour guide.

We proceeded eastward down the Susa valley past the spectacular Fort Exilles. About 24 km west of Turin we turned north and climbed on a winding road through misty rain to the Col del Lis pass, then twisted down north-eastwards to Germagnano near Lanzo in the Lanzo valley. This was our base until August 10 when we moved to Domodossola, west of Lake Maggiore.

August 5th we stopped at several interesting localities between Col del Lis and Germagnano. On the 6th we had the most rewarding (for me) moments of the entire tour when we examined layering in the Lherzolite on the Lanzo River near Lanzo. A vigorous discussion of the origin of the layering developed into a discussion of the origins of ultramafic rocks in general and lherzolites in particular, and these discussions continued through the succeeding days. On the 7th we traversed more layered lherzolite in Tese Creek then visited the nearby Baldissero massif.

The 8th and 9th we spent with Dr. Dal Piaz from Turin and these tours will be discussed separately. On the 10th we returned to Lanzo lherzolite for another stimulating half day, then drove to Domadossola via Turin and Lake Maggiori.

On the 11th we examined the Finero massif which includes garnetiferous gabbro and pyroxenite, and on the 12th inspected the Alpi Arrami garnet peridotite and eclogite locality. The tour party disbanded on 13th, most to proceed to Prague for the International Geological Congress.

The aluminous peridotites

The peridotite bodies in this region contain significant CaO and Al_2O_3 and thus may be fragments of primary mantle. Differences in mineralogy between the various bodies may reflect differences in depths of crystallization. Thus (a) the Lanzo massif may have crystallized at shallow depth (say 20 km) because plagioclase is a stable component, (b) the Baldissero massif probably crystallized at moderate depth because plagioclase is lacking (CaO and Al_2O_3 are held in pyroxenes and spinel), and (c) the Alpi Arrami massif crystallized at great depth to produce garnet peridotite.

The simple explanation of the origin of the ultramafic rocks is complicated by the fact that in at least two cases (Lanzo and Baldissero) the ultramafics are associated with significant volumes of gabbro and basalt.

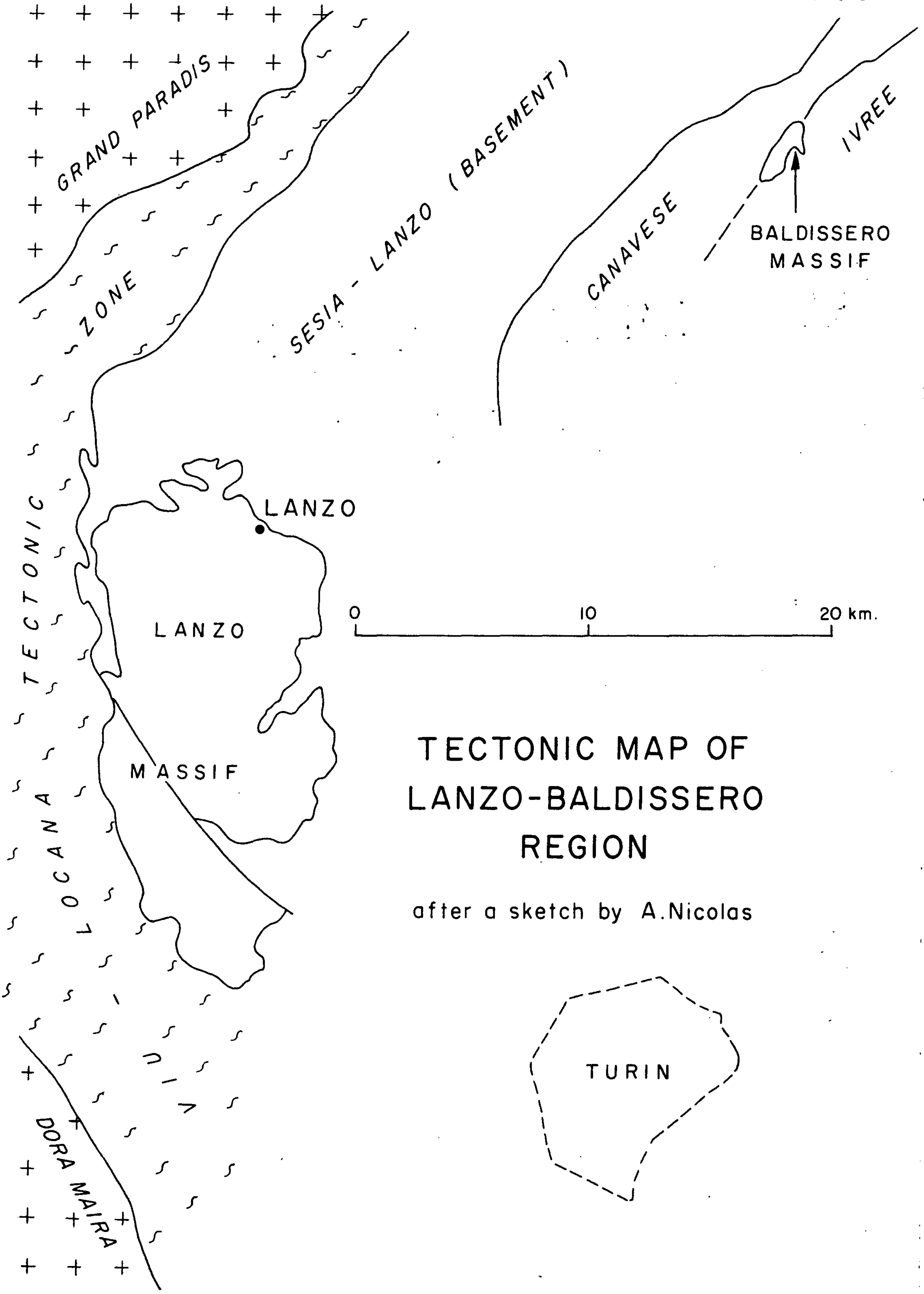
Regional geology

Dr. Nicolas has spent a number of years studying the area between Dora Maira and Grand Paradis in the piemontaise Alps, (Nicolas, 1966a, and b, 1967, 1968). The main geological elements of the region are the older crystalline massifs of Dora Maira and Grand Paradis to north and south, the nappes of Mesozoic Schistes lustrés and ophiolite in the west, the Viu-Locano tectonic zone (N-S) in the centre and the Lanzo lherzolite in the east.

Nicolas (op.cit.) has suggested that the lherzolite was emplaced as part of a massive flow of lherzolite, gabbro, and basalt, into Schistes lustrés sediments in Mesozoic time. However, I understand that he now favours subcrustal origin of the lherzolite, and emplacement by faulting. In either case the lherzolite and the other ophiolitic rocks probably rose along the Viu-Locano tectonic zone.

The Viu-Locano tectonic zone was also the locus of westward basement over-thrusting which produced flat-lying nappes in the Mesozoic (Schistes lustrés and ophiolite) cover. Dr. Nicolas showed us a prasinite (greenschist after basalt) exposure which bore evidence of two tectonic events: 1. the thrusting mentioned above which took place at the end of the Eocene, and 2. a later folding which produced east-west recumbent isoclinal folds. The first event caused the development of glaucophane; the second event disrupted whatever orientation the glaucophane may once have had, and produced a greenschist facies mineral assemblage. A third event, the retro-charriage or reverse thrusting, was not in evidence at the localities which we visited.

Plate 5



TECTONIC MAP OF LANZO-BALDISSERO REGION

after a sketch by A.Nicolas

To accompany Record 1969/47

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LANZO LHERZOLITE AND ASSOCIATED GABBRO AND BASIC SCHIST

(AFTER NICOLAS 1967)

- gb — Gabbro
- s s — Serpentinite
- (hatched) — Lherzolite
- ∧ ∧ ∧ — Schist after basalt (prasinite)

Schistes lustrés and older crystalline rocks not shown

N

0 — 8 Km

0 — 5 M

Lanzo lherzolite

The Lanzo lherzolite is about 30 x 15 km and consists of an unserpentinized core with a serpentinite rim; layering strikes generally near N-S, and dips towards the centre of the body; a northwest right-lateral fault, connected to the Viu-Locano tectonic zone, displaces the southern part of the body.

The lherzolite is unusual in that it typically contains some plagioclase.

Average composition is:

olivine (Fo_{91})	60 percent
enstatite (Mg_{87}, $FeMn_{9.5}$, Ca_3)	15-20 percent
diopside (Mg_{50}, Ca_{44}, $FeMn_6$)	6-10 percent
labradorite An_{62}	6-8 percent
chromiferous spinel	2 percent

Layers within the lherzolite consist of concentrations of clinopyroxene and plagioclase. Some of the layers are pseudo-veins i.e. they have sharp contacts; others are gradational concentrations. Plagioclase grains are aligned within the layers. Immediately below most of the plagioclase-rich layers there is a plagioclase and diopside-free zone up to six inches thick, as though these minerals had concentrated in layers by migrating upwards. We discussed the origin and nomenclature of the layers at length. The favoured hypothesis of origin was that proposed by Dr. Jackson. An original mantle rock consisting of olivine and aluminous pyroxene is faulted into the crust and at say 20 km depth and is partially melted; this allows plagioclase to develop. Layering parallel to the stress field is produced at this stage.

Baldissero lherzolite

The Baldissero massif is about 3 x 1 km and lies about 25 km northeast of Lanzo. It has the same bulk chemical composition as typical Lanzo material, according to Dr. Nicolas, however it differs from Lanzo in containing no feldspar. This indicates that it crystallized at greater depth.

Finero massif

The Finero massif is about 25 km east of Domadossola and is enclosed in the older crystalline gneisses of the Ivrea Zone. It is an aluminous peridotite which is thought to have been recrystallized during the Hercynian? orogeny, and subsequently subjected to K-metasomatism.

The typical ultramafic rock consists of olivine, enstatite, chrome amphibole, and spinel; some peridotite contains phlogopite which is thought to be of metasomatic origin. Associated with the ultramafics is an about equal thickness of layered gabbro which consists of garnet, plagioclase, hornblende, and some pyroxene. At their contact the gabbro and peridotite are interlayered. Discussion centred around whether seemingly porphyroblastic garnets which are thought to have developed by metamorphism of gabbro, might instead be primary components of a garnet-pyroxene mantle rock, that breaks down to garnet-plagioclase-pyroxene as it rises through the crust.

I did not record any literature references for Finero but Dr. Nicolas advised that a student, Lensch, from Saarbruck University is currently studying the area.

Alpi Arrami massif

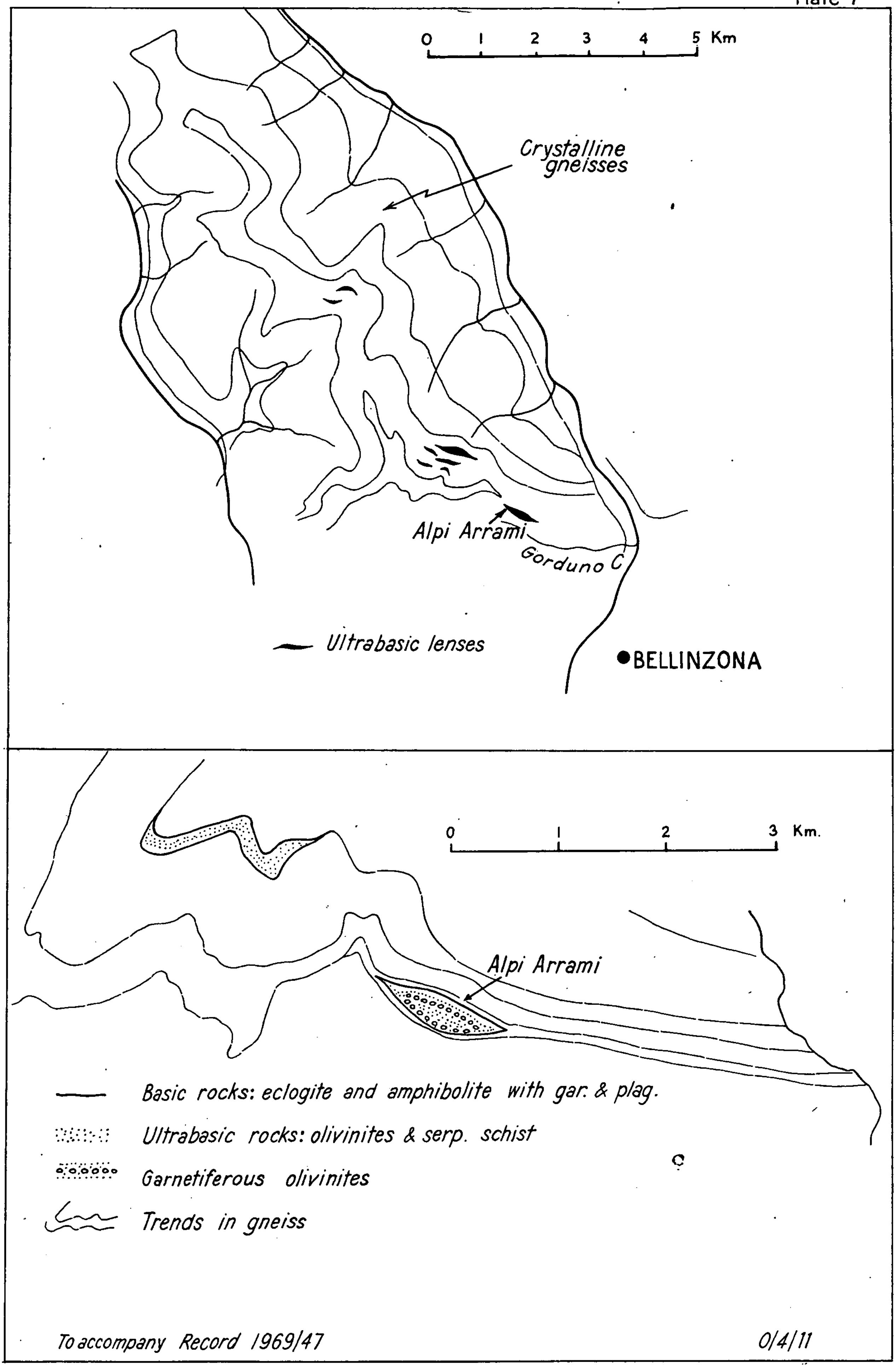
The Alpi Arrami garnet peridotite is a lens, measuring about 300 x 1000 m, in crystalline gneisses more or less along strike north-east of Finero and about 5 km north-west of Bellinzona in Switzerland (Canton Ticin). It has been described by Dal Vesco (1953) and is currently being studied by a student, Mockel, from Amsterdam; O'Hara and Mercy (1966) have analysed rock samples from Alpi Arrami and conclude that it may represent primary mantle.

The lens consists of foliated lherzolite with two horizons of garnet-lherzolite, patches of garnet-clinopyroxene rock (eclogite) and clinopyroxene rock, the whole enveloped by kyanite eclogite (Dal Vesco,op.cit., as reported by O'Hara and Mercy,op.cit.). O'Hara and Mercy (op.cit.) found that the garnet peridotite and lherzolite have high Al_2O_3, CaO, Na_2O, K_2O and TiO_2, as might be expected if they represent primary mantle. The garnet-clinopyroxene rocks are anomalous because they are poor in Na_2O and Cr_2O_3 and enriched in Fe/Mg relative to the garnet and pyroxene of the adjacent garnet peridotite.

ALPI ARRAMI GARNET PERIDOTITE

After Dal Vesco (1953)

Plate 7



VAL D'AOSTA: AUGUST 8 - 9

Leader: G.V. Dal Piaz

Participants: As for the garnet peridotite excursions

In the course of a geological mapping programme north of the Aosta valley, 100 km north of Turin, Dr Dal Piaz has made a particular study of rodingite inclusions in the various serpentinites (Dal Piaz, 1967). He has been able to demonstrate that most were originally gabbroic dykes, and not contact metamorphic skarns as some previous workers had suggested. He proposes that the common term for these rocks: "granatiti" (garnetite), be abandoned because in many cases garnet is not strongly developed.

We visited Champoluc and Perreres (Valtournanche) which is locality No. 10 in his report (op.cit.) and examined a great variety of rodingites. Typical minerals are grossularite, vesuvianite, diopside, epidote, clinozoisite, and chlorite. Garnet is very coarse-grained in some cases. Above Champoluc we saw euhedral garnet and chlorite formed apparently by metasomatism of gabbro, and nearby an outcrop of clinohumite-bearing schist.

The scenery in this area is spectacular, for the Matterhorn stands immediately north of Valtournanche, and on the second day we were high enough to examine a receding glacier. From Verres, lower in the Val d'Aosta, we examined magnificent exposures in the near-vertical walls of the valley. Dr Dal Piaz pointed out the older Gneiss Minuti (Crystalline basement) thrust north-westward over Mesozoic Schistes lustrés.

DOMADOSSOLA - ZURICH - PRAGUE - LONDON

Our group went their separate ways on August 13. We proceeded to Zurich via the Totalp serpentine (lherzolite) near Davos in Graubunden. This has been described by Peters (1963) and compared with the lherzolite of Lherz in the Pyrenees (Peters and Niggli, 1964). Both contain layers of ariegite, a garnet-two-pyroxene-spinel rock.

In Zurich we re-organized, sent off the accumulation of literature and rock specimens by surface mail and prepared for the next stage of the trip, the International Geological Congress in Prague.

We flew to Prague on August 16 and spent the weekend absorbing the local scene and preparing for the forthcoming sessions. The Czechs distributed the full proceedings of the Congress to us upon registration so there was much to read. Monday 19th the Congress opened with an official welcome and scientific addresses, and Tuesday the meetings began in earnest.

I attended Upper Mantle Geotectonics meetings on Tuesday. These opened with a paper by Beloussov advocating vertical versus horizontal tectonics and a greater emphasis on land as opposed to submarine geology. This drew a lengthy rebuke from Wilson and in turn a defense by Beloussov which were to be the highlights of the morning. In the afternoon a palaeomagnetic review by Creer which contained interesting material was spoiled by his attempt to crowd an hour's address into 20 minutes allowed.

Wednesday morning we awoke to the sound of aircraft; four-engine turbo-prop transports were taking off regularly with a flight path over our residence. I thought nothing of it and switched on our portable radio to pick up Voice of America news. We were stunned to hear that Russian tanks had crossed the border shortly before midnight and that Prague was now occupied. It was hard to believe but the truth was brought to us emphatically as we took the morning bus to the congress. Armoured troop carriers passed us as we made our way towards the city and as we approached the Technical University we found tanks singly and in groups on the major streets. A steady stream of tanks, armoured cars, and trucks hauling mortars, filed through the Square of the October Revolution, in front of the University.

I decided to attend the Upper Mantle meetings that morning and hear an interesting paper on the Rhine Graben: the graben can be traced from the Upper Rhine north and north-westwards into the North Sea. However it was difficult to concentrate on geological discussion with such sad and momentous events outside besides which many of the scheduled speakers were not present. (The U.S. Embassy had advised all the American geologists to stay in their hotels.) I left the meeting at about 11.00 and after discussing the situation with others gathered as much food as I could lay my hands on and returned to the Hostel on foot by a devious route.

It was generally considered that it would be several days or perhaps weeks before the occupying forces would allow us to move. However next morning (Thursday) a road convoy was organized with an escort of official cars from the U.S. and Swedish embassies. A stranger offered us a ride which we accepted gratefully and so, after seven hours on the road, we reached the West German border. From the border the U.S. Army took us by bus to Nuremberg and there we bedded down at about 2 a.m., after wiring relatives and B.M.R. to advise our safe arrival. The other delegates were able to make their way safely out of Prague by train and car on Friday and Saturday.

We rested Friday and flew to London on Saturday 24th August. We were scheduled to reach London on 28th so had an extra four days available. This we utilized to visit the Lizard peridotite in Cornwall. We hired a car in London on Wednesday 28th and spent Thursday and Friday at the Lizard, in the company of John Milsom. The following week Milsom and I worked on a joint paper on the geology and gravity of eastern Papua, and we left London for New York on September 5.

The Lizard peridotite

D.H. Green of the A.N.U. made a study of the Lizard peridotite while a student at Cambridge University (Green 1964a, b). Previous studies had been made by J.S. Flett (1946) of the Geological Survey. We armed ourselves with these publications and the One-mile geological map of the area, which is No. 359: Lizard (Falmouth) in the Geological Survey series.

Green had advised me to visit the west coast cliffs from Mullion southwards to see contact relations between peridotite and host metamorphics. Also we wanted to see the gabbro-peridotite contact at Coverack, for Thayer (1967) has argued that the gabbro is probably related to the peridotite and any hypothesis which seeks to explain the origin of one should explain the origin of the other.

The Lizard peridotite is an aluminous lherzolite which was emplaced in solid state at high temperature during a period of amphibolite facies metamorphism. The peridotite is zoned from coarse-grained aluminous lherzolite in the centre to cataclastic plagioclase-bearing lherzolite at the margins. Core and margin have the same chemical composition; the different mineral compositions are due to crystallization at different confining pressures. The recrystallized rim is locally hydrated to produce pargasite and serpentine.

In summary:

Core	Anhydrous rim	Hydrous rim
olivine	olivine	olivine
Al enstatite	normal enstatite	normal enstatite
Al diopside	normal diopside	pargasite
Al spinel	a different spinel	serpentine
	plagioclase (labradorite)	brown Cr spinel

(Green, 1964a). The metamorphic aureole around the peridotite is a thermal effect superimposed upon the regional metamorphism. Successive zones of the aureole are characterized by brown-green hornblende, hornblende with hypersthene and augite, and ultimately hypersthene-augite granulite. In places the granulite host has become more mobile than the peridotite and intrudes and includes blocks of granulite (Green, 1964b); we inspected one such instance in the cliffs just north of Pol Cornick, south of Mullion.

The gabbro and troctolite at Coverack, on the east coast, are intrusive into peridotite. Green (1964a) argues that they are probably not related to the peridotite because olivine and pyroxenes in the peridotite differ in major and trace element composition from those in the gabbro and troctolite. I lean towards Thayer's (1967) argument that the worldwide association of gabbro with peridotite bodies such as this (admittedly not all aluminous) is a powerful argument for the proposition that the two are genetically related. Accordingly any hypothesis of origin for the peridotite should also provide for the origin of the gabbro.

Thayer (op.cit.) also suggests that the hypersthene-augite granulite of the metamorphic aureole is in fact a gabbro related to the peridotite. Our examination of the exposures at Pol Cornick coupled with Green's (1964b) exhaustive study of these rocks convince me that the granulites are metamorphic.

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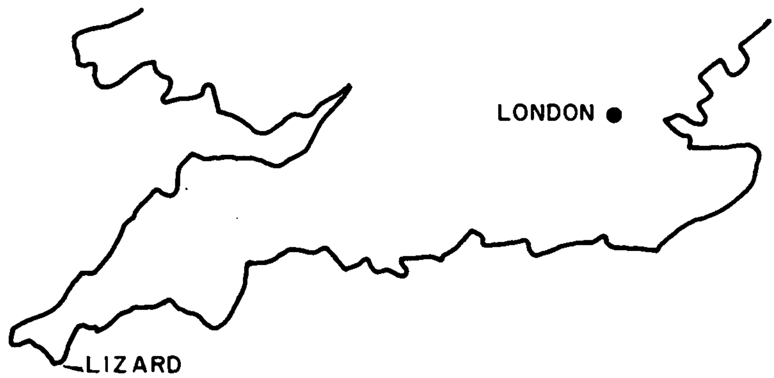
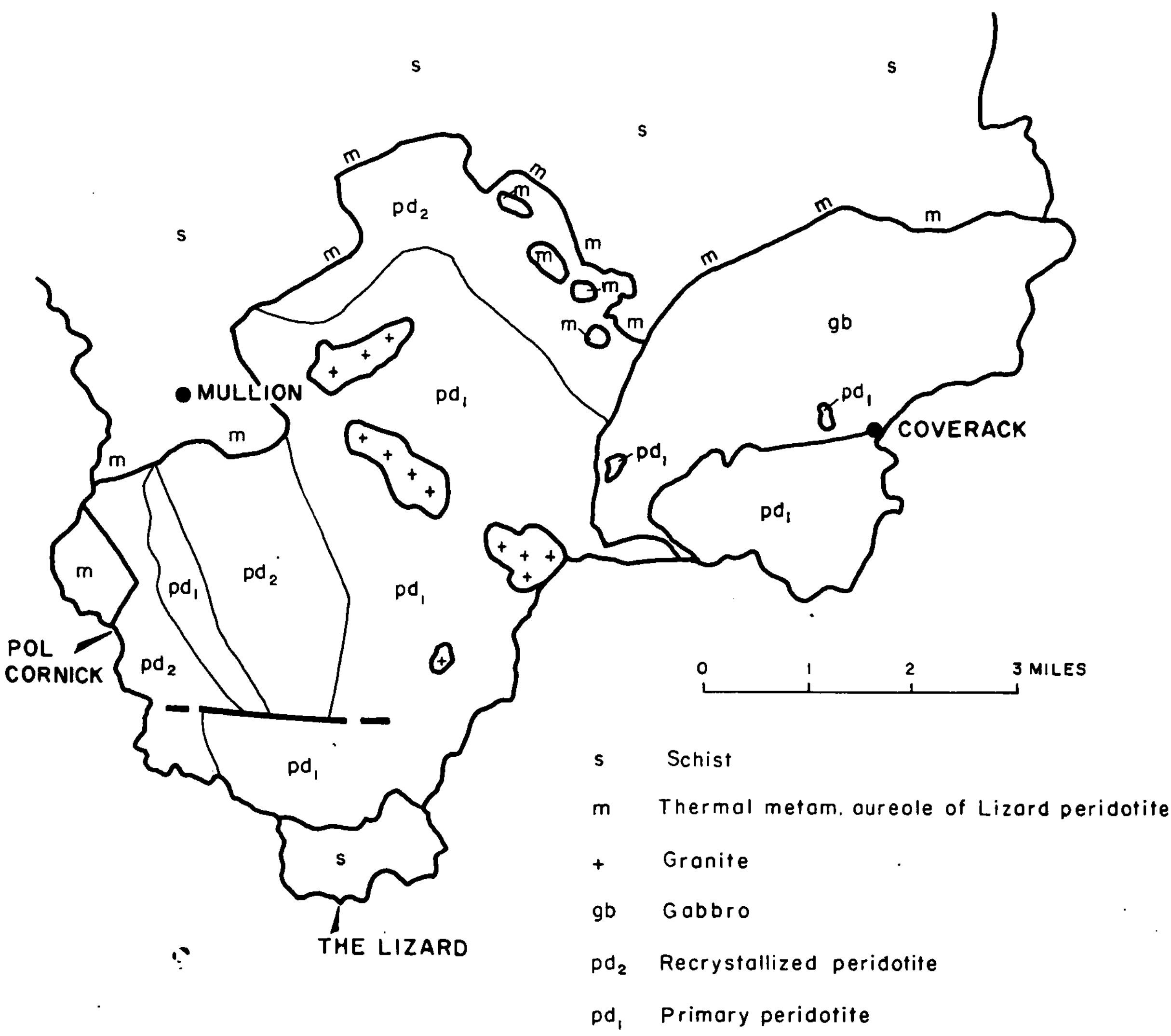
LIZARD PERIDOTITE

after D.H.Green (1964a)





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