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EXOTIC NAPPES IN EXTERNAL PARTS OF OROGENIC BELTS

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ABSTRACT. In many orogenic belts, large nappes or thrust sheets, often preserved in klippen, overlie parts of the more standard fold-and-thrust belts that form the external zones of the orogens. Commonly the stratigraphic sequences in these nappes cover all or a large part of the same time span as the strata in the underlying fold-and-thrust belt but are of a very different—"exotic"—facies evidently deposited somewhere else, presumably in more internal parts of the orogenic belt. In most cases the strata of the fold-and-thrust belt were deposited in shallow water on continental basement near the continental margin, whereas those in the overlying nappes represent deeper water, commonly starved sequences. In certain regions, several such nappes are superposed; in some such regions one of the highest nappes includes ultramafic rocks—ophiolite—probably representing part of the oceanic crust on which some of the exotic sedimentary sequences were deposited. In certain cases the exotic materials were actually intercalated like "sediments" into the highest part of the underlying, more "normal" stratigraphic sequence and then underwent its later deformational history.

Some of the youngest examples of such nappes (for example, the Prérif of Morocco, the argille scagliose or Ligurian ensemble of Italy) seem to have been displaced into their "exotic" position at least partly by gravity (sliding or spreading), from uplifts in internal zones of the orogenic belt into downwarped parts of its external zones. In older examples (for example, the Préalpes, the Taconic klippen), the rôle of gravity is more equivocal, and more "standard" subterranean thrusting may account for much or all of the displacement.

By exotic nappes[1], I mean nappes or thrust sheets whose stratigraphic section is quite foreign to the stratigraphy of underlying, relatively autochthonous rocks of the same age, though those rocks too are commonly thrust forward as part of a typical décollement fold-and-thrust belt of the kind I described in earlier articles of this series (Rodgers, 1990, 1991). In each case, to be sure, the hypothesis that they are in fact nappes had first to be proposed and demonstrated; for the Préalpes that was accomplished nearly a century ago, but for a few of the others the debate continues. Once they were accepted as nappes, the chief argument has been about how they were emplaced, whether surficially by gravity sliding or spreading—mass wasting, generally considered as submarine—or along subterranean, "hard-rock," thrust faults resulting from "ordinary" orogenic compression; indeed in some cases a combination—

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[1] I use the word "nappe" for a body of rock that was translated laterally at least 5 km (3 miles) over other, "autochthonous" or "parautochthonous," rocks. The word can be used whatever the probable cause of the translation—gravity (rootless) or compression (rooted).

first compression, then gravity sliding—is by no means ruled out. A further question has been the source region—the "roots" or *patrie*—whence came the exotic rocks that overlie the relatively autochthonous strata in the fold-and-thrust belt. In several of the examples it appears that they came from beyond a zone of external massifs that lies behind the fold-and-thrust belt, probably from a suture zone near the margin of but within the metamorphic core of the orogenic belt. Figure 1 is a cartoon of this situation, inspired by actual cross sections drawn by others for each of the four principal examples here described.

I come by my interest in such nappes or thrust sheets honestly, for I was born, brought up, and introduced to geology in Albany, New York, which is within sight of the main Taconic slate mass and is partly built on minor masses and blocks of the same rocks ("blocks-in-shale," "Wildflysch breccia") that lie in front of that mass. Even before I went to college, Dr. Rudolf Ruedemann, the great graptolite expert of his generation in North America, had given me some inkling of the fascinating stratigraphic and structural puzzles posed by the Taconic slates, puzzles that he was among the first to recognize and work at and that I have come back to again and again, notably in graduate school when I heard from Professor Carl O. Dunbar about the stratigraphy of western Newfoundland (Schuchert and Dunbar, 1934) and later when I read, only half comprehending it, Professor Marshall Kay's seminal paper on palinspastic maps (1945). The critical moment in my understanding, however, was the field excursion into the Rif of northern Morocco before the 19th International Geological Congress in Algiers in 1952. For that reason I have chosen the Prérif nappe rather than the Taconic klippe as my type example.

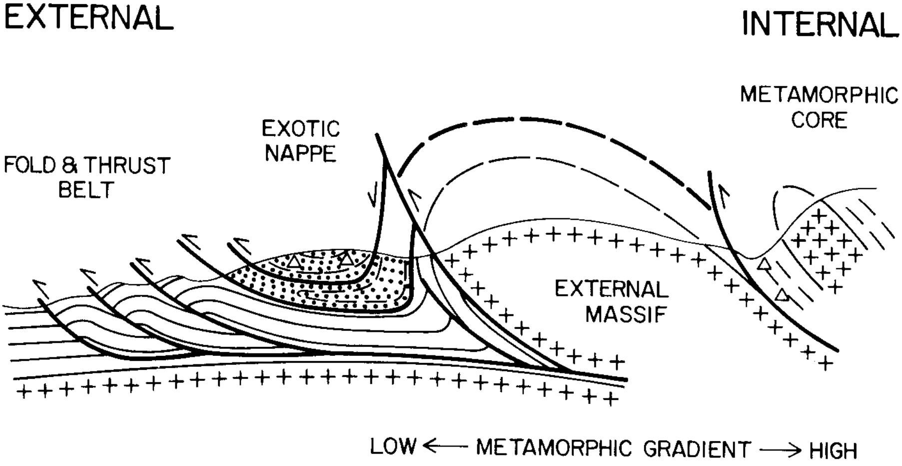

Fig. 1. Cartoon to show situation of "exotic nappes" (stippled) in relation to other structural zones in the external parts of orogenic belts. Triangles indicate regions where ultramafic rocks might be expected; crosses represent basement.

Generalized (to the point of caricature) from cross sections drawn by others: for the Prérif, Lévy and Tilloy, 1952, plate 5; for the Préalpes, Bearth and Lombard, 1954, Carte et coupes géologiques; for the northern Apennines, Elter, 1980, fig. 3.1; for the Taconic region, Doll and others, 1961, section D-D′.

A TYPE EXAMPLE—THE PRÉRIF NAPPE OF NORTHERN MOROCCO[2]

Morocco (fig. 2A) extends across three major geologic regions (see also Rodgers, 1987, fig. 6A, p. 682):

1. on the south, the Saharan or West African Precambrian craton (with, at the west, the northern extension of the Mauritanide orogenic belt, Mu[3]),

2. in the center, a wide Variscan orogenic belt including the Anti-Atlas (AA), the High Atlas (HA, rejuvenated in germanotype style during the Cenozoic; see Rodgers, 1987, p. 684), the Middle Atlas (MA), and the "Moroccan Meseta," and

3. on the north, the Alpine, alpinotype Maghrebide orogenic belt along the south coast of the Mediterranean Sea—the Moroccan part of that belt is the Rif.

In this article we are concerned only with the western part (fig. 2B) of the Prérif (PR), an east-west belt up to 80 km wide (wider in the subsurface along the Atlantic coast) that forms the southern margin of the Rif in western Morocco from the Atlantic Ocean eastward 250 km to beyond Taza (T on fig. 2A; 50 km east of the east edge of fig. 2B). The Prérif was studied intensively by la Société chérifienne des Pétroles during the 1940s and 1950s (Société chérifienne des Pétroles, 1952; Lévy and Tilloy, 1952; Bruderer and Lévy, 1954; Burger, Housse, and Lévy, 1962), using detailed mapping, paleontology (especially foraminifera), and drilling. The present discussion is based on that work.

The Prérif belt is bounded on the south by two structural provinces within the general Variscan orogenic belt (fig. 2A, region 2), to the east by the broad arch, mainly in Mesozoic strata, of the Middle Atlas (a mild example of a cratonal uplift; Rodgers, 1987, p. 684), and to the west by the "Moroccan Meseta," whose deformed Paleozoic rocks, cut by granite, appear from beneath widespread, mostly flat-lying Mesozoic and Cenozoic strata.

The Mesozoic succession in these provinces is platformal and of variable thickness, reaching several kilometers in certain basins (notably in the South Rif basin north of Meknès); the platform was established on the stabilized Variscan orogenic belt. Largely non-marine Triassic with abundant evaporites is overlain by marine Jurassic limestone, marl, and sandstone (roughly in that order). Close to the Prérif belt, the Cretaceous, chiefly Upper Cretaceous, is thin, sporadic, and incomplete, mainly carbonate and phosphatic marl, the last reaching into the Paleocene; otherwise Lower Cenozoic strata are absent, but both Cretaceous and Lower Cenozoic are much more nearly complete farther south in the region of the "phosphate plateau" (the phosphate there ranges from uppermost Cretaceous to lower Eocene). Neogene and Quaternary

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[2] The English name Morocco, like the name for the country in other European languages, applies to the country the name of one of its principal cities, Marrakesh (M on fig. 2A; the accent is on the second syllable); the country's official name, in Arabic, is Maghreb, the West or the sunset.

[3] Initials in parentheses refer to figure 1 of Rodgers, 1991.

deposits overlap all older rocks down to Lower Paleozoic; the Miocene, mainly marine marl with sandstone at base and top, thickens northward toward the Rif, reflecting a downwarping of the north margin of the platform, whereas the Pliocene and Quaternary thicken westward toward the Atlantic Ocean and include terrace gravels and dune sands as well as shallow-marine deposits, reflecting the gradual retreat of the ocean. The west end of the Prérif itself is buried under the alluvial plain of the Rharb (or Gharb), a large filled-in lagoon, but drilling, especially in its southern part, provides considerable information on the rocks below the alluvium.

This platformal cover, otherwise flat-lying except where broadly folded in the Middle Atlas, is sharply broken, in a zone 50 km long along the south edge of the Prérif belt, by several thrust slices called the Prérif wrinkles (PR; les rides prérifaines[4]); they are not continuous enough to add up to a typical fold-and-thrust belt, though they show some of the characteristics of such belts. They trend west and verge south, but at their west ends the two largest swing abruptly through northwest to north (or northeast) and continue for 25 km "across strike;" apparently the western one turns north as it approaches the abrupt west or northwest margin of the South Rif Mesozoic basin. Despite considerable argument at first, drilling has shown that they have listric or sled-runner geometry and are entirely thin-skinned, the décollement being in the Triassic evaporites. They also involve the whole Miocene section and appear to have moved in the early Pliocene. As they bring up the marine Jurassic limestone, which is quite resistant to erosion, they make conspicuous cuestas or hogbacks rising above plains underlain by flat-lying Cenozoic strata. About 25 and 35 km farther east, two short isolated slices of the same kind appear in the region north of Fes.

North of the Prérif wrinkles is the Prérif zone (which includes the Prérif nappe and the Miocene above and below, see fig. 2B), a belt of low smoothly rounded hills largely underlain by marl—limy mudstone or muddy limestone—in which landslips are very common; it is difficult to work out the geology of such weak, poorly exposed, incessantly sliding "rocks." Nevertheless, as the result of very detailed mapping supplemented by an immense number of foraminiferal determinations from washed samples, the surface geology is now reasonably well known. It was first displayed on a map (Société chérifienne des Pétroles, 1952) presented to the Rif excursionists in 1952; an inset on the map summarizes the subsurface data as well (fig. 2B of this article; plate 1 of Lévy and Tilloy, 1952).

At first sight, the geology of the Prérif zone looks impossibly chaotic. The largest part—forming the matrix as it were for the rest—is Cretaceous marl with some bodies of sandstone (flysch), in good part contemporaneous with the platform Cretaceous to the south, as exposed in the Prérif wrinkles, but of a quite different, deeper water facies; no very

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[4] More recently these structures have been renamed les rides sud-rifaines, to avoid confusion with la zone prérifaine just to the north (Faugères, 1981).

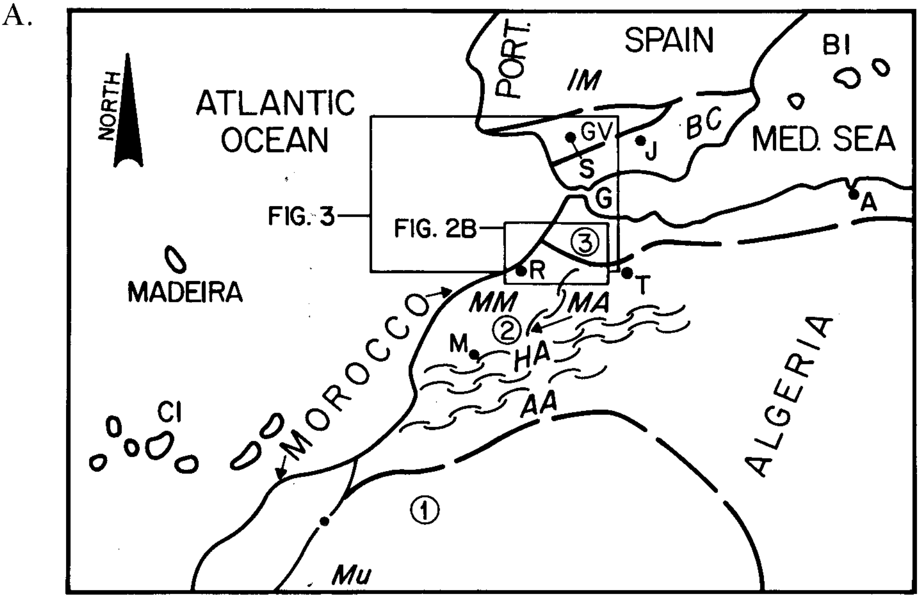

Fig. 2(A) Sketch map of Morocco and the surrounding regions, showing the three major geological regions of the country (numbers 1-3 in circles) and the locations of (B) and figure 3.

1—West African craton
Mu—northern extension of Mauritanide orogenic belt, here the Zemmour Noir
2—Variscan orogenic belt
AA—Anti-Atlas Range
HA—High Atlas Range
MA—Middle Atlas Range
MM—"Moroccan Meseta"
3—western part of Maghrebide orogenic belt: Rif in Morocco, Tell in Algeria
Other letters:
A—Algiers (Algeria)
BC—Betic Cordillera (southern Spain)
BI—Balearic Islands (to Spain; from west to east: Ibiza, Majorca, Menorca)
CI—Canary Islands (to Spain)
G—Gibraltar
GV—Guadalquivir Valley (Spain)
IM—Iberian Meseta (Spain and Portugal)
J—Jaen (Spain)
M—Marrakesh (Morocco)
R—Rabat (Morocco)
S—Sevilla (Spain)
T—Taza (Morocco)
Continuous line—coast line
Line with dot—eastern edge of West African coastal plain (shown only in southern Morocco)
Heavy dashed line—boundary of geological region
Overlapping short curves—mountain range in Variscan orogenic belt of Morocco

Fig. 2(B) Structural sketch of western Prérif and the Rharb, northwestern Morocco, reproduced from Lévy and Tilloy, 1952, plate 1.

Legend (translation):
Pliocene-Quaternary reclaimed marsh-land
Lacustrine limestone
Miocene covering the nappe
Prérif nappe
Miocene beneath the nappe
Mesozoic
Paleozoic
Granite

Note: The concentric circles show the rock units cut by the drill-holes, successively from the outside (highest) to the inside (lowest) [as if one were looking down the drill-hole and were seeing the units on its walls and bottom].

B.

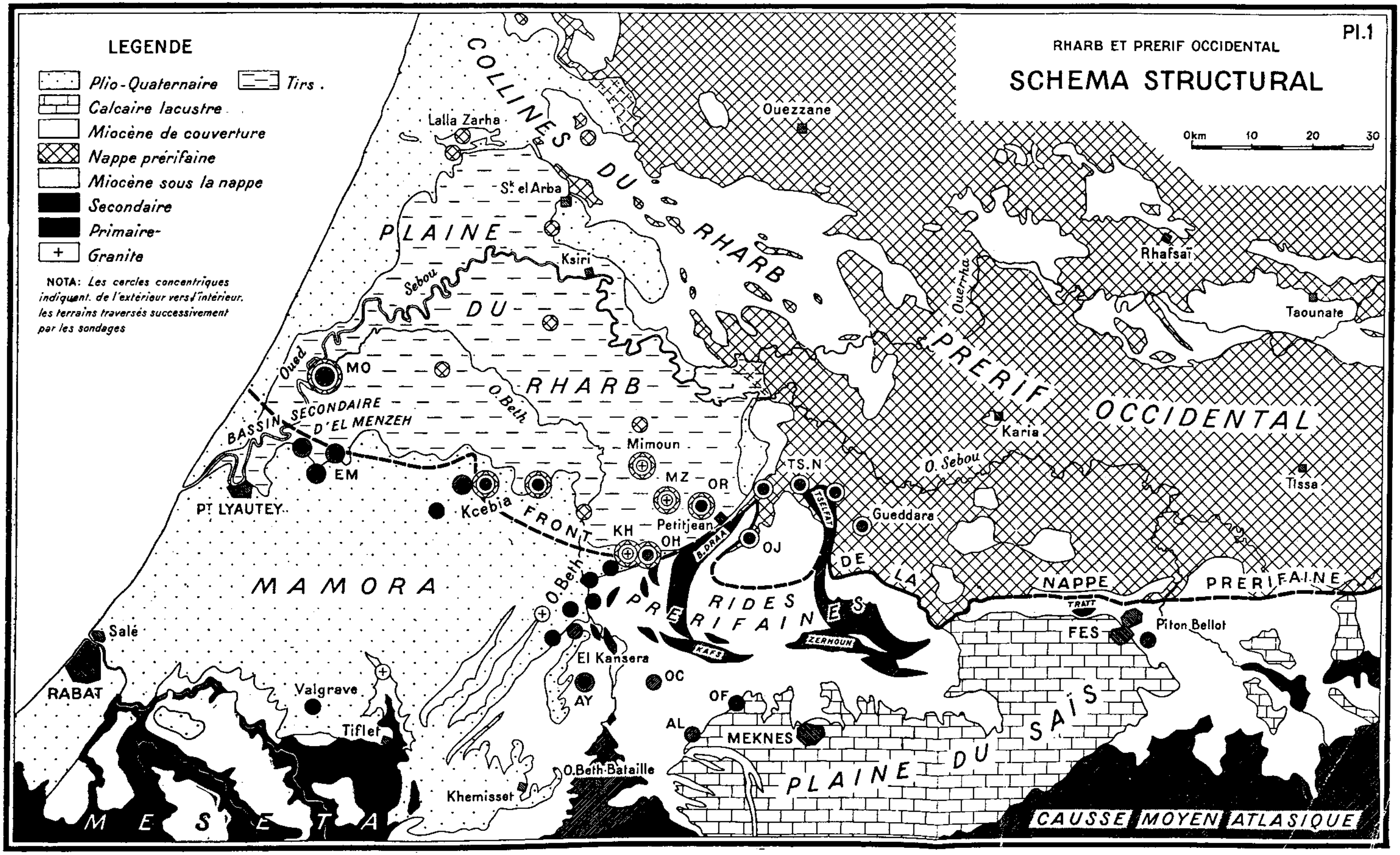
Pl.1
RHARB ET PRERIF OCCIDENTAL
SCHEMA STRUCTURAL
0km 10 20 30
LEGENDE
Plio-Quaternaire
Tirs.
Calcaire lacustre
Miocène de couverture
Nappe prérifaine
Miocène sous la nappe
Secondaire
Primaire
Granite
NOTA: Les cercles concentriques indiquent de l'extérieur vers l'intérieur les terrains traversés successivement par les sondages
COLLINES DU RHARB
PLAINE DU RHARB
PRERIF OCCIDENTAL
BASSIN SECONDAIRE D'EL MENZEH
MAMORA
FRONT DE LA NAPPE PRERIFAINE
RIDES PRERIFAINES
PLAINE DU SAÏS
CAUSSE MOYEN ATLASIQUE
MESETA
Lalla Zarha
Sk el Arba
Ouezzane
Ksiri
Sebou
Oued
O. Beth
MO
Rhafsaï
Taounate
Ouerrha
Karia
O. Sebou
Tissa
Mimoun
MZ
OR
TS.N
TSELFAT
Gueddara
Petitjean
KH
OH
OJ
B. DRAA
EM
Pt LYAUTEY
Kcebia
O. Beth
KAFS
ZERHOUN
TRATT
FES
Piton Bellot
Salé
RABAT
Valgrave
Tiflet
El Kansera
AY
OC
OF
AL
MEKNES
Khemisset
O. Beth Bataille

Figure 2B

obvious large-scale structure can be deciphered in it. Scattered irregularly through it are masses of reddish sediments associated with evaporites and thoroughly altered mafic rocks ("ophites"), the standard Triassic assemblage in all the external belts of the western Mediterranean Alpine chains.[5] Jurassic rocks are absent except near the northern margin of the Prérif belt, near the adjacent southern part of the main Rif, which is made of more conventional nappes or thrust sheets formed of various Lower Cretaceous and uppermost Jurassic flysch units (leaving out of account the Oligocene "Numidian" flysch in a highest nappe). In the northern Prérif, Lower Jurassic carbonates form a series of isolated mountains up to several kilometers on a side, called sof—a local Berber word that apparently means fort, for they stand high above the surrounding rolling landscape and are commonly cavernous, so that they make ideal forts; I was assured that the word sof is used only for such Jurassic blocks. Up to the Jurassic, therefore, the "succession" in the Prérif is not unlike that on the platform but, as already noted, the Cretaceous is quite different.

Also "swimming" in the Cretaceous marl are basin-like synclines or brachysynclines of Paleogene strata (Eocene to Oligocene), including not only marl but also nodular and cherty limestone below and flysch above, less chaotically arranged than the Mesozoic rocks around them. The synclines are a few kilometers wide but rarely over 20 km long and mostly shorter; their limbs are generally steep, not uncommonly overturned and cut by thrust faults—in some both limbs are overturned, producing "tobacco-pouch" forms. In shape and plan these synclines remind me of giant load-casts of somewhat more competent strata dropped into the underlying very plastic mud and mudstone; Tilloy (Lévy and Tilloy, 1952, p. 21) compared them to icebergs. As noted above, Paleogene strata are virtually lacking on the north margin of the adjacent platform, and farther south they are shallow-water deposits, very different from those in the Prérif synclines, whose facies suggests deeper water, far at first from any source of coarse clastics. Thus the Cretaceous-Paleogene sequence in the Prérif zone seems to have been deposited in a basin or trough north of the platform margin on which the incomplete sequence exposed in the Prérif wrinkles was deposited. Finally, recent discoveries of Miocene foraminifera show that some, perhaps much, of the "matrix" marl is of that age, also worked into the Cretaceous.

During the heyday of the nappe theory in the early twentieth century, when it was being applied everywhere after its spectacular success in the Alps, the Prérif zone (omitting the Prérif wrinkles) was described as a Prérif nappe, but in the later reaction an autochthonist view prevailed. The detailed studies of la Société chérifienne des Pétroles, especially its drilling (Bruderer and Lévy, 1954; Lévy and Tilloy, 1952;

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[5] Another element treated as a sort of "guide fossil" for the Triassic in these regions is doubly terminated quartz crystals a centimeter or so long. Such crystals are known in evaporite-mudstone sequences of various ages in several parts of the world—for example, the Jurassic Gypsum Springs formation in Wyoming and adjacent states—but here they seem to be exclusively in the Triassic.

Burger, Housse, and Lévy, 1962), resuscitated and confirmed the nappe hypothesis, at least in the southern part of the zone. In some 20 holes in that region (some shown on fig. 2B), Cretaceous marl of the nappe or basin facies, with or without Triassic or Paleogene rocks, rests upon fossiliferous Miocene strata, which are also mostly marl and which in turn rest either on the platformal Mesozoic with its very different Cretaceous or directly on deformed Paleozoic strata or Paleozoic granite. The fossils, mainly foraminifera, show that the top of the autochthonous sequence is upper Middle Miocene, Tortonian. On the other hand, many holes (including some of the same ones), as well as surface exposures, show that the allochthonous marl is overlapped by other Miocene strata, sandy or even conglomeratic toward the north, whose foraminifera are also Tortonian, just younger than the strata below; these upper strata may be called neoautochthonous. Where both top and bottom of the nappe are encountered in the same drill hole, its thickness ranges from a few hundreds of meters to 3 km; in other holes farther north, thicknesses of several kilometers have also been drilled, although the base was not reached. But south of a quite definite line (shown on fig. 2B), drill holes encountered an unbroken section of Miocene marl showing no discordance at the level in the Tortonian where the nappe is intercalated north of the line, only a sandy facies that decreases southward (Bruderer and Lévy, 1954, p. 293). Thus the nappe is a blunt wedge, inserted at a specific stratigraphic level as if it were a part of the normal Miocene sequence and thickening northward at some tens of meters per kilometer (the data are too scattered to make this figure precise). That after Tortonian time the nappe had become simply a wedge within the Neogene stratigraphic succession is shown by its being involved, along with the Miocene strata both below and above, in the north-trending western ends of the two largest Prérif wrinkles mentioned above (p. 177), which formed later, quite unaware that they were punching up through an exotic nappe.

The lack of deformation in the Miocene strata even close to the nappe front (except where they are deformed by the later Prérif wrinkles) and the incompetent nature and chaotic arrangement of the "rocks" within the nappe show that it was in no sense a conventional, subterranean, "hard-rock" thrust sheet and were indeed among the reasons for the earlier skepticism about the nappe hypothesis. The data now available demand, however, that the basinal deposits are exotic in their present position over the platform margin, having arrived in the Tortonian sea from some source or *patrie* to the north beyond the Cretaceous edge of the platform (though probably not its Early Jurassic edge); the drill holes prove a minimum displacement of 20 km, and the strong facies differences suggest several times that. I therefore accept the hypothesis (Lévy and Tilloy, 1952, p. 20-21) that they arrived as a giant mudflow, kilometers thick, on the floor of the deepening Miocene sea, impelled by gravity. Badoux (1967, p. 404) cites the Prérif nappe and the similar Carmona nappe (next page) as examples of olistostromes.

How they were uplifted out of their basinal source high enough to flow tens of kilometers southward over the originally higher platform is much less clear. A reasonable hypothesis, not contradicted by what is known of the timing, is that, when the several flysch nappes in the southern part of the main Rif were thrust forward and piled upon one another, they compressed the basin to their south and squeezed upward and southward its exceptionally incompetent and plastic contents, which flowed as a gigantic mud-slide into the Miocene sea, while the much more competent Jurassic limestone formed isolated blocks that moved less easily and less far than the rest.

The interpretation of the Prérif zone as wholly a gravity slide has been challenged in recent years (Wildi, 1983, p. 218; Favre, 1992; Favre, Stampfli, and Wildi, 1991, p. 55-58). Work in the belt along and south of the border between the "typical" Prérif and the flysch nappes to the north (a belt sometimes called the Meso-Rif) has shown that the larger and more continuous areas of Jurassic limestone there form small but coherent thrust sheets, partly related to the lowest nappe in the main Rif, the Ketama nappe (*not* a "flysch nappe" like those farther north). That work has also shown that some bodies of chaotic material here are overlapped by older Miocene deposits; apparently whatever process produced the chaotic deposits operated at least twice during the Miocene, but only the last such deposit spread into the southern Prérif region. The evidence along the southern margin of the Prérif, as cited above, convinces me that this last deposit was emplaced by gravity (mass-wasting), but farther north, in the Mesorif, we may be observing the (diachronous?—polyphase?) transition from emplacement by compression to emplacement by gravity flow.

THE CARMONA NAPPE OF SOUTHERN SPAIN

There is a remarkable even if not perfect mirror symmetry between the mainly south-vergent Maghrebide orogenic belt on the south coast of the western Mediterranean, or at least its western part, the Rif, and the mainly north-vergent Betic Cordillera orogenic belt (Be) on the north coast in southern Spain (see fig. 2A) and east through the Balearic Islands of Ibiza and Mallorca (but not Menorca). In southeastern Spain and in Ibiza and Mallorca, the external zone is the Pre-Betic; it is (part of) a reasonably typical fold-and-thrust belt (the rest is the Sub-Betic zone or part of it), though with some characteristics that recall the Jura. Westward around Jaen, 250 km northeast of the west end of the Betic Cordillera at the Atlantic coast, the Pre-Betic zone disappears beneath the post-orogenic Neogene and Quaternary fill of the Lower Guadalquivir basin, whose north side laps up unconformably on the south margin of the Iberian Meseta, made of Paleozoic rocks deformed and metamorphosed in the Variscan orogeny. A Mesozoic platform cover is preserved at the surface of the Meseta only at the two ends of that margin, but it is also known by drilling beneath the west end of the Lower Guadalquivir basin.

Although the present surface of the Lower Guadalquivir basin is clearly Quaternary alluvium, the main filling is marine clastic Miocene, thickening southward to several kilometers and becoming coarser southward and upward. Intercalated in the Burdigalian-Helvetian (Lower Miocene-lower Middle Miocene) part of this section are masses of Cretaceous marl (with some Triassic?) very much like that in the Prérif nappe but almost entirely underground; they were first discovered by drilling (Perconig, 1962, p. 244-245, 249-251, 254-256) in the region around Carmona, 30 km east of Sevilla and 100 km from the Atlantic coast, and have been called the Carmona nappe. (The few poor exposures add nothing to our understanding.) The symmetry with the Prérif is startling, though the timing is a little different. The source area must be well to the south (probably behind the Subbetic zone), presumably under the flysch nappes of the Campo de Gibraltar, which have much in common with the flysch nappes of the Rif and are apparently continuous with them around the arc of Gibraltar.

Even more remarkably, seismic profiling of the sediments beneath the Atlantic Ocean west of Gibraltar (fig. 3; Lajat and others, 1975) suggests that the Carmona and Prérif nappes are actually confluent there and may extend in a narrowing wedge for 400 km west from the Straits of Gibraltar, ending on an abyssal plain. It appears moreover that this immense nappe or olistostrome becomes younger westward and may still be moving near its western tip.

THE PRÉALPES

Geographically within the Helvetic zone of Switzerland (He) and the northeast end of the Subalpine zone of France (Su) (Rodgers, 1990, p. 332-340, fig. 3) are several masses of mainly Mesozoic rocks whose stratigraphy shows that they have nothing to do with the normal Helvetic-Subalpine sequence upon which they lie. By far the largest such mass forms the Préalpes (fig. 4A, following p. 188), a mountainous area 120 km long and up to 35 km wide astride the upper Rhône, which divides it into les Préalpes du Chablais, mainly in France, and les Préalpes romandes, in Switzerland. For 90 km to the northeast in central Switzerland (fig. 4B), a series of much smaller outliers of some of the same rocks forms isolated mountains, always nested in a frontal syncline of the Helvetic zone; these are the original Klippen (Swiss-German for cliffs). Around them other less resistant non-Helvetic rocks cover considerable areas. A last remnant lies 50 km farther on, just short of the Rhein and the east border of Switzerland. There are also two such masses south of the west end of the Préalpes in a syncline in the northern Subalpine zone in France. The history of discovery of the complex geological structure of the Préalpes is admirably reviewed by Masson (1976).

The Mesozoic and Lower Tertiary strata in these areas clearly belong to several coeval sequences with distinctly different facies, each of which must have come from a different basin or part of a basin of deposition. Basement rocks are rare but do occur as slivers or blocks at the bases of a couple of the sequences. All these rocks clearly overlie the normal Helvetic-Subalpine strata tectonically, and they form a whole series of nappes emplaced above the nappes and folds of the Helvetic-Subalpine zone (herein called the HeSu zone; for a summary of its stratigraphy, see Rodgers, 1990, p. 333, 336).

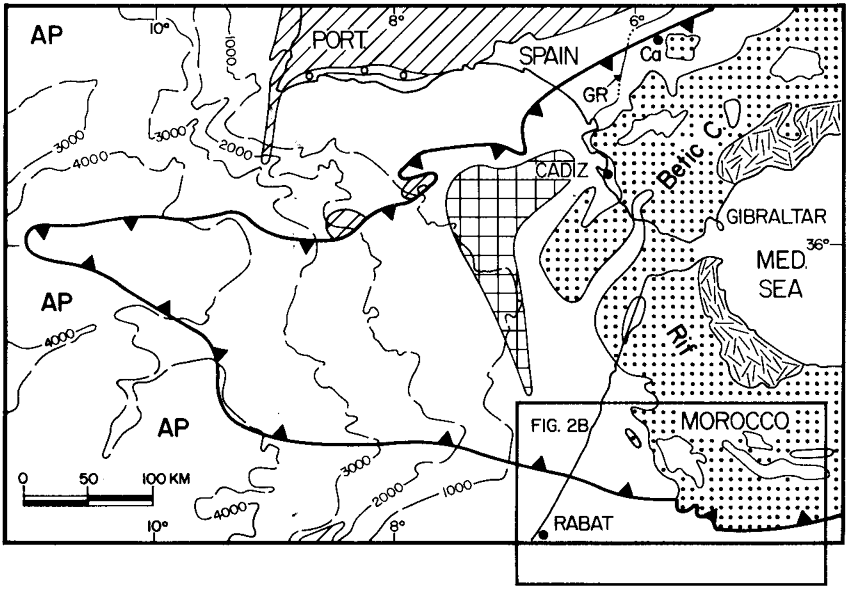

Fig. 3. Relation of the Betic-Rif arc or arc of Gibraltar to the ocean-floor deposits to the west. Redrawn from Lajat and others, 1975, figure 1.

Light continuous line—coast line
Light dashed line—submarine contour, in 1000's of meters
Heavy line with filled triangles—limit of allochthonous nappes (nappe de Carmona, Prérif nappe)
Blank—post-orogenic (late Miocene and younger) deposits
Cross-hatched—zone with diapirs
Stipple—external zone of Betic and Rif (including flysch nappes)
Random dashes—internal zone of Betic and Rif (including Dorsale calcaire)
Open circles (only one area)—outcrop of undeformed Tertiary and Mesozoic resting on Paleozoic of Iberian Meseta
Diagonal lines—Paleozoic of Iberian Meseta and exposures of pre-Mesozoic rocks on the sea floor
Letters:
AP—abyssal plain on floor of Atlantic Ocean;
Ca—Carmona
GR—Guadalquivir River
Box—area of figure 2B.

The lowest and most widespread such sequence is called Ultrahelvetic; it differs from the Helvetic in containing much more marl. The Triassic evaporites are conspicuously present in many areas, and the uppermost Jurassic Tithonian limestone is also present, though generally thinner and more obviously pelagic than in the HeSu zone; on the other hand, the Lower Cretaceous shallow-water "Urgonian" limestone is conspicuously absent.

Because the Ultrahelvetic strata are largely incompetent, nonresistant rocks, their structure is difficult to decipher and locally approaches the chaotic, but in the region near the upper Rhône, especially along the south side of les Préalpes romandes, they have been divided by careful mapping and detailed stratigraphic work into several different thrust sheets or nappes, stacked one over another (Badoux, 1963). (One might indeed cavil at calling them nappes because of their relatively small size compared to the Helvetic nappes below and the higher nappes in the Préalpes above.) Each nappe is distinguished by its own stratigraphic limits and succession but, when they are taken as a whole, they appear to be parts of a single body of sediments deposited in an asymmetric basin (see Badoux, 1963, fig. 3, p. 12; Homewood, 1976, fig. 8, p. 291). In that basin, in addition to some facies changes, a disconformity beneath lowest Tertiary or upper Upper Cretaceous strata bevelled down into the older strata as far as the lower Middle Jurassic (if not locally the Triassic and the basement, to judge by blocks of granite and other rocks in the strata next above the disconformity). The hiatus increases from the external to the internal side of the basin (from original northwest to original southeast), and the total thickness decreases from a kilometer or so in the external part to perhaps 300 m in the internal part.

Furthermore, as the different Ultrahelvetic nappes moved northwestward to form the stack, they did so rather systematically; the first to move, now the lowest, were composed of the higher part of the basin, the last, now the highest, of the thinner, bevelled, sequence in its internal part. The resulting inversion of the stratigraphy during nappe emplacement was recognized by Lugeon (1943), and he called the process "diverticulation"[6]. (For further definition of this term, see Badoux, 1967, p. 404-405.)

When the Helvetic nappes in the HeSu zone were forming, probably diachronously, the Ultrahelvetic nappes were being emplaced above them (Masson, oral communication, 1993). As in the case of the Prérif nappe above the Prérif wrinkles, they were then folded as if they formed an integral part of the Helvetic stratigraphic succession. Thus Ultrahelvetic strata (belonging to more than one of the Ultrahelvetic nappes) are preserved beneath the anticlinal cores and thrust slices of some of the Helvetic nappes, most conspicuously in western Switzerland between the nappe de Morcles below and the nappe des Diablerets above. Such an insertion of a higher nappe beneath a lower one is called involution (German: Einwicklung). The complex structure thus formed was decipherable because of the strong contrast in facies between correlative Lower Cretaceous "Urgonian" shallow-water limestone in the Helvetic sequence and Lower Cretaceous "Néocomien à Céphalopodes" deeper water marl in the Ultrahelvetic sequence.

[6] The concept of diverticulation has been attacked recently (Burkhard, 1988, p. 102, 107), and recent work suggests that the upper units commonly reckoned to the Ultrahelvetic zone are actually more closely related to the overlying Niesen nappe (see below, p. 188), the infra-Niesen zone of Escher, Masson, and Steck (1987, p. 10). The concept of diverticulation seems viable still, however, for the remaining Ultrahelvetic units, those associated with the Helvetic nappes (Masson, oral communication, 1993).

Above the Ultrahelvetic units, the main bulk of the Préalpes is considered a single nappe, des Préalpes médianes (German: Klippendecke, for the original Klippen in central Switzerland, of which it forms the largest part), but it includes two rather different stratigraphic sequences, characterized by Lugeon and Gagnebin (1941, p. 44f.) from their effect on the later deformation as les médianes plastiques and les médianes rigides. (For me, they are at least as deserving of being distinguished as separate nappes as the several Ultrahelvetic units, but the literature does not do so.) The lateral changes in the stratigraphic sequence of les Préalpes médianes are described and depicted by Baud and Septfontaine (1980) in the form of a palinspastic reconstruction.

The stratigraphic sequence in les médianes plastiques has some characters in common with the Ultrahelvetic sequence, notably the presence of much marl and a distinct Tithonian limestone unit, and indeed some authors concluded that the two sequences were deposited in a single large basin, but other characters (such as the absence of the Upper Cretaceous disconformity) and regional considerations indicate deposition in different basins. The lower part of the sequence, which is all marine after the usual Upper Triassic with evaporites, is thicker than in the Ultrahelvetic zone (up to 2 km), but the Upper Cretaceous, Paleocene, and lower Eocene are made of a thin, somewhat interrupted, succession (100 to 200 m) of entirely pelagic muddy limestone or marl, generally stuffed with foraminifera showing that most of the constituent stages are represented, some however only by foraminifera trapped in crusts ("hard-grounds") formed during periods of no deposition. The marl is variegated—gray, green, pink, and red; from the last, these strata are commonly called "couches rouges," though red is generally minor. They are succeeded by equally thin Middle Eocene black shale with a few intercalations of impure sandstone, which is called "flysch noir" though it's a pretty poor flysch. The whole marly, mostly incompetent sequence is thrown into relatively tight folds with few obvious faults, the style being controlled mainly by the relatively competent Tithonian limestone near the middle.

The lower part of the sequence in les médianes rigides is totally different. The Triassic, though it includes evaporites especially along the basal thrust (and in a few places a bit of presumably Lower Triassic quartzite below that), is largely thick competent limestone with some dolostone (500 m or more), which can be shown by rather rare fossils to be Middle Triassic (Upper Triassic is probably present also, but as unfossiliferous dolostone) and which is quite unlike anything in any of the sequences observed to the (original) north as far as and including the European platform Mesozoic north of the Alps. Upper Upper Triassic and Lower Jurassic strata are missing, and the Middle Jurassic, where present, is in a peculiar shallow- or brackish-water facies of black shale with *Mytilus*—it even includes coal in places. The Upper Jurassic is represented only by non-typical, shallow-water Tithonian limestone. Lower Cretaceous is missing, but the pelagic "couches rouges" are present, as thin as ever or even thinner, and not necessarily starting with the Cenomanian as they generally do in les médianes plastiques. In places the only indications of lower Upper Cretaceous deposition are foraminifera trapped in karst-like cracks or depressions in the underlying Jurassic or Triassic carbonate; the first continuous bed above may be upper Upper Cretaceous or even Paleocene or Eocene. An exiguous "flysch noir" caps the succession.

The presence of a thick carbonate buttress between thin evaporites below and a rather thin marly succession above has produced a very different structure from that in les médianes plastiques. The carbonate forms great rigid blocks (see Baud, 1972, fig. 1) in each of which the sequence is clear but which seem to have jostled by one another like giant two-by-four boards, punching down into les plastiques beneath and even more up into and even over the nappes that originally overlay them. One smaller block at St.-Triphon in the Rhône valley now lies quite flat, but the succession is entirely inverted, as shown by Jeannet already in 1911 (Jeannet and Rabowski, 1912, p. 241) and confirmed by Badoux (1962).

The two sequences, plastiques and rigides, clearly reflect a basin of deposition and an adjacent carbonate bank, both far from land, for no detrital clastics other than fine mud are present between the lowest part of the Triassic and the Eocene.

But this is not all. Above the Préalpes médianes comes la nappe de la Brèche or Brecciendecke, which forms a broad syncline in les Préalpes du Chablais but narrower strips in les Préalpes romandes, caught beside and under blocks of les rigides. Its stratigraphic sequence (again between 1 and 2 km thick), though beginning with Upper Triassic (more like les plastiques than les rigides) or even with slivers or blocks of pre-Mesozoic basement, is characterized by a full Jurassic succession of dark, mainly deep-water shale (calcareous or siliceous, the latter with radiolaria), but it includes thick units of carbonate breccia, the fragments clearly being derived from the carbonate bank of les médianes rigides. The Tithonian is represented not by limestone but by an upper unit of the breccia; the Lower Cretaceous is mainly pelagic cherty limestone but is often absent. The Upper Cretaceous and Paleocene are "couches rouges" again, and the sequence ends with "flysch noir." Clearly this sequence was deposited in a basin next to a steep (faulted?) margin of the carbonate bank.

The rocks above la nappe de la Brèche form the tectonically highest units in the Préalpes and have been variously classified into one nappe (Simmendecke, nappe Supérieure des Préalpes) or more, up to four (Caron, 1972). One unit (Caron's highest, nappe des Gets) is characterized by blocks of the ophiolite suite, using the term in Steinmann's original sense of serpentine and pillow lava associated with radiolarian chert (not the current definition that demands the "stratigraphy" of the oceanic crust, though these rocks probably came from an oceanic basin); indeed it was Steinmann (1905, p. 37-38, 64-65) who first clearly recognized this separate, highest nappe. The other units are characterized by their various Upper Cretaceous flysch units (locally as old as Albian, upper Lower Cretaceous).[7] One of these flysch units consists in good part of fine-grained carbonate, mainly in graded beds with quartz sand present at the base of the graded units; the upper surfaces of many of the beds are marked by distinctive worm tracks called helminthoids. Not much of these highest units has been left by erosion, but Trümpy and Bersier's classic study of the Oligocene molasse conglomerate in front of the Préalpes (Trümpy and Bersier, 1954) shows that at that time fully half the source area being eroded belonged to the Simmendecke, s.l. Probably the flysch units were deposited in a basin, part of whose floor is represented by the ophiolite unit.

Another flysch nappe, made of the Upper Cretaceous to Lower Tertiary Gurnigel flysch (perhaps the most "typical" of all the Alpine flysches) and correlative units, is found as several large masses all along the northwest, external margin of les Préalpes médianes (plastiques) and also northeastward beside some of the klippen. As it overlies Ultrahelvetic rocks, it was long reckoned to the Ultrahelvetic (Préalpes externes), but Caron (1976; also Homewood, 1974, p. 396-397) has shown that it is another part of this highest nappe group, probably related to Caron's lowest nappe in the group, and that it passed beyond the others and was caught (in part involuted) beneath la nappe des Préalpes médianes.

An additional complication is the Niesen nappe, which consists largely of upper Upper Cretaceous (mainly Maastrichtian) carbonate flysch, commonly conglomeratic (there is also some Eocene flysch), resting disconformably on small slices of earlier Mesozoic rocks or nonconformably on pre-Triassic basement. The flysch is intensely folded, and many of the folds show strongly curved axes. Moreover the Niesen nappe shows low-grade metamorphism (of the other Prealpine nappes, only la nappe des Gets shows any metamorphism, and that is even lower grade). It lies in a single long belt along the southeast side of les Préalpes romandes, resting upon the Ultrahelvetic units but molded as it were against the back of the pile of higher nappes.

Clearly associated with and tectonically overlying the Niesen nappe is the Zone submédiane; when first recognized (McConnell and de Raaf, 1929, p. 101, 108-111), it was described as simply an upper slice of the Niesen nappe, but more recently (Weidmann and others, 1976) it has been considered an independent nappe. It is largely a mélange (of mixed sedimentary and tectonic origin, according to Weidmann and others, 1976, p. 275)—a matrix of gypsum or scaly shale with blocks of varied provenance, mainly from the Niesen nappe below but partly from les Préalpes médianes (especially les rigides) to the side; indeed some of the smaller blocks of les rigides are swimming in it.

Those who considered that the Ultrahelvetic units and les médianes plastiques were deposited in a single basin of deposition have found the

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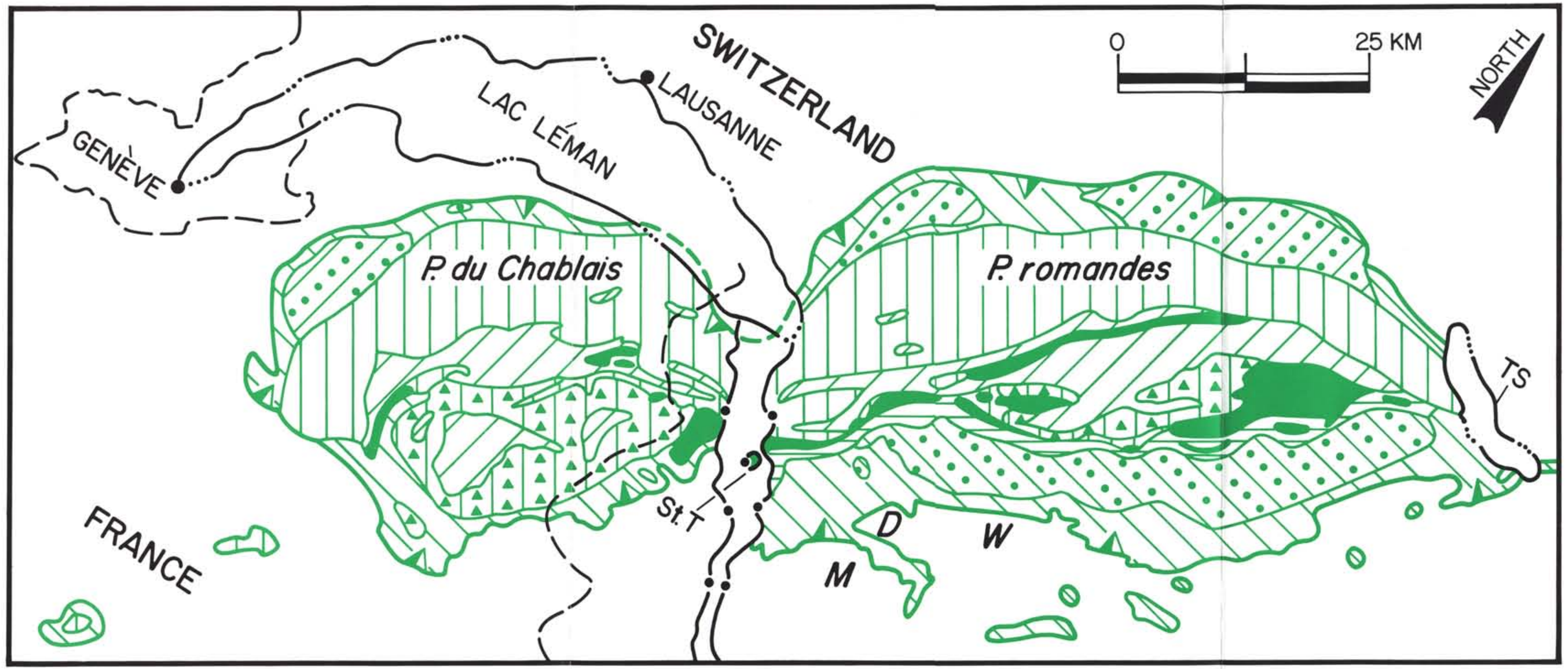
[7] For a long time, all flysch in the Alps was supposed to be Tertiary, as it is in the HeSu zone, but some of the most typical examples are now known to be partly Cretaceous.

Fig. 4(A) Schematic tectonic map of the Préalpes, Switzerland and France, based on Tectonic Map of Switzerland (Spicher, 1980).

Dashed black line: international border (France-Switzerland)
Black line with three light dots: shore of lake
Black line with heavy dots: border of alluvium, upper Rhône
Green lines tilted to right: nappes supérieures des Préalpes—Simmendecke, s.l.
Green lines tilted to right separated by lines of dots: nappe du Gurnigel (part of nappes supérieures)
Green vertical lines separated by lines of filled triangles: nappe de la Brèche—Brecciendecke
Solid green: Médianes rigides } nappe médiane des Préalpes—Klippendecke
Green vertical lines: Médianes plastiques } nappe médiane des Préalpes—Klippendecke
Green horizontal lines: nappe submédiane
Green lines tilted to left separated by lines of dots: nappe du Niesen—Niesendecke
Green lines tilted to left: nappes ultrahelvétiques
Light green line: boundary between Prealpine units
Heavy green line with half-filled triangles: outer margin of the Prealpine nappes
Blank: Structural units beneath the Prealpine nappes
Letters:
D—Nappe du Diablerets (Helvetic)
M—Nappe de Morcles (Helvetic)
St T—Saint-Triphon
TS—Thunersee (Lake of Thun)
W—Nappe du Wildhorn (Helvetic)

Fig. 4(B). Index map showing location of the Prealpine klippen and related units in the western Alps.

Light line bordered with stipple: coast of Mediterranean Sea
Light line with three dots: river or lake-shore
Heavy line with heavy dots: limit of alluvium in Po valley
Heavy dashed line with single ticks: outer limit of Alpine deformation in the Jura
Heavy dashed line with double ticks: outer limit of Alpine deformation in the Alps proper
Heavy line with filled triangles, or heavy circle or oval: front of Pennine zone (bordered by green strip) and limit of Prealpine and other klippen (solid green)
Light continuous line: limit of basement in external massifs
Line of black circles: zone Briançonnaise, in Pennine zone
Box: Location of 4(A)
Letters:
AM—Aar massif
B—Belledonne massif
Ba—Basel
BH—Barrhorn
Br—Briançon
BS—Bodensee (Lake of Constance)
Fh—Nappe du flysch à helminthoïdes
Ge—Genève
Gn—Genova
GO— Gotthard massif
HE—Helvetic zone
LL—Lac Léman (Lake of Geneva)
MA—Mercantour-Argentera massif
MB—Mont Blanc (and massif)
MC—Mont Chétif
N—Nice
P—Pelvoux massif
Sa—Savona
Sc—Schams
U-E—Nappe de l'Ubaye-Embrunais
V—Vanoise
Z—Zürich



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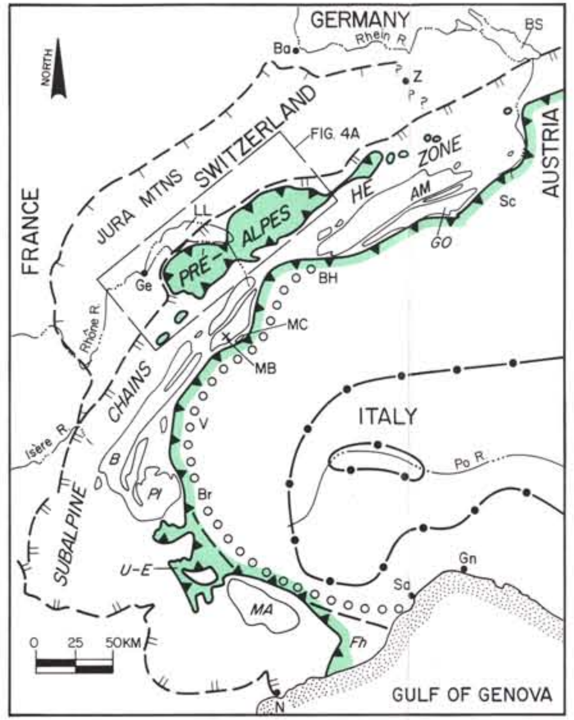


B.

Fig. 5(A) Schematic tectonic map of northern Apennines, based on Modello Strutturale d'Italia (Consiglio Nazionale delle Ricerche), 1971, supplemented by articles, especially Merla, 1961; Elter, 1975a, 1980)

Light continuous line: coast line

Light line with three dots: River Po

Medium dashed line: watershed of Apennine Range

Heavy dots: international boundary, Italy-San Marino

Filled circle: city—

Ar—Arezzo
Bb—Bobbio
Bo—Bologna
Ca— Carrara
Fe—Ferrara
Fi—Firenze (Florence)
Fo—Forli
Gn—Genova (Genoa)
Li—Livorno (Leghorn)
LS—La Spezia
Lu—Lucca
Ma—Mantova (Mantua)
Mo—Modena
Pa—Parma
Pc—Piacenza
Pi—Pisa
Pv—Pavia
Ra—Ravenna
Re—Reggio Emilia
Ri—Rimini
Sa—Savona
Si—Siena

Other letters:

AA—Alpi Apuane
AS—Adriatic Sea
MP—Monte Pisano
SM—San Marino
TS—Tyrrhenian Sea
VM—Voltri massif

Black line with open triangles: buried thrust fault in upper Cenozoic sediments beneath Po alluvium

Overlap facies (in black):

Blank: post-orogenic sediments unconformable on transported, deformed rocks—Middle Miocene to Recent on southwest side, Pliocene to Recent on northeast

Random dashes: epi-Ligurian basins—synorogenic sediments unconformable on transported, deformed rocks but themselves transported and deformed—Upper Eocene to Middle Miocene

Ligurian facies (in green):

Green horizontal lines: Monte Antola nappe—flysch à helminthoïdes—Upper Cretaceous

Green lines tilted to right: Monte Gottero-Val Lavagna nappe ("arenarie superiore," scisti di Val Lavagna)—Jurassic to Cretaceous

Heavy green lines tilted to right: Bracco nappe—ultramafic and mafic rock, associated with sedimentary rock that includes ultramafic fragments and olistoliths—Jurassic to Middle Cretaceous

Green vertical bars: Voltri massif—ultramafic and mafic rock and associated sedimentary rock—Jurassic to Cretaceous

Green vertical lines: Monte Caio, Monte Cassio, Monte Sporno nappes and related units—largely flysch à helminthoïdes—mainly Upper Cretaceous but with considerable Paleocene-Eocene along northeast side

Light green lines tilted to left: disturbed complex or complesso caotico—commonly chaotic ("argille scagliose")—matrix mainly Cretaceous, blocks of many ages

Medium green lines tilted to left: Nappe de Canetolo—olistostromes of higher Ligurian nappes below, flysch-like sandstone above—Paleocene to Lower Miocene (shown only in Bobbio window)

Heavy green line with half-filled triangles: base of Ligurian facies or ensemble

Tuscan facies (in black):

Middle Cenozoic flysch:

Heavy black vertical lines: entirely Miocene (marnoso-arenacea)

Medium black vertical lines: mainly Miocene, some Oligocene (nappes of Cervarola, Falterona)

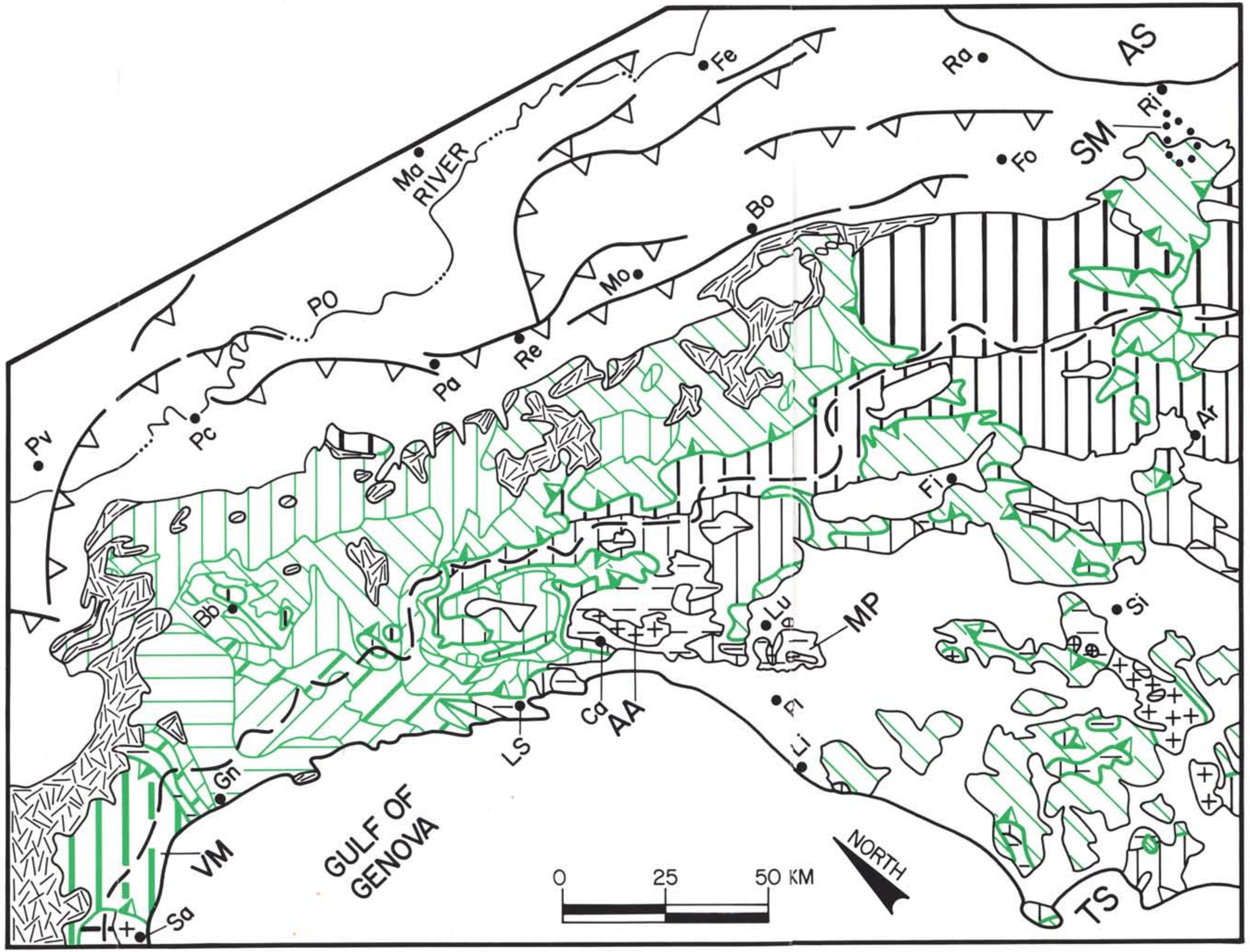
Light black vertical lines: mainly Oligocene, some Lower Miocene (macigno)

Pre-flysch rocks (metamorphic on lowest sheet)

Black horizontal dashes: sedimentary strata—Oligocene to Middle Triassic (not shown everywhere)

Black crosses: Pre-Mesooic basement

Heavy black horizontal line: Briançonnais zone in Savona axis



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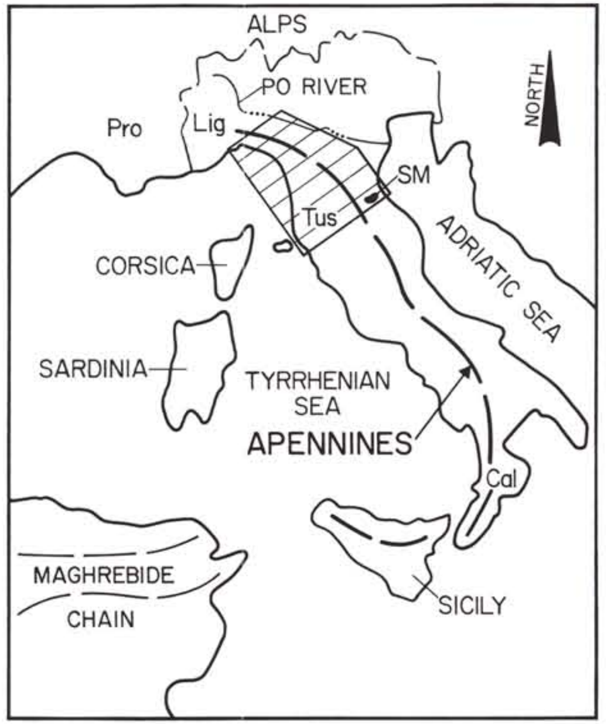

B.

Fig. 5(B) Map of Italy showing location of (A).

Letters:

Cal—Calabria
Lig—Liguria
Pro—Provence
SM—San Marino
Tus—Tuscany

Niesen nappe inexplicable. In some respects, however, it is like an intensification of the higher Ultrahelvetic units, the highest of which were at one time not distinguished from it—a sort of Ultra-Ultrahelvetic sequence in which the Upper Cretaceous disconformity that increases from the lower to the higher Ultrahelvetic units reaches its maximum. The source of the limestone clasts is not clear, but presumably they came from the core area of the uplift recorded by the disconformity, which may once have separated the Niesen basin from that of les médianes plastiques where there is no trace of the disconformity or of upper Upper Cretaceous conglomerate (limestone conglomerate in the French equivalent is Jurassic).

Thus the Prealpine nappes record a very complex paleogeography during the Mesozoic in the area southeast (present direction) of the carbonate platform represented by the Helvetic nappes beneath. The first basin, the Ultrahelvetic, was starved, and its internal part was uplifted in late Cretaceous time. The Ultrahelvetic nappes root on or behind the Gotthard basement massif, southeast of the Aar massif (Ar; Rodgers, 1995, p. 465 ff.), and behind Mont Chétif, a tiny basement slice just southeast of Mont Blanc (MB)—in other words, along the northern border of the Pennine zone, now the metamorphic core of the Alps. The Niesen nappe probably came from the lower Pennine or Simplon zone in that core; the last to get away, it was singed by the beginning of the metamorphism that the others escaped.

A furious debate once raged over the source of la nappe des Préalpes médianes or Klippendecke, for the thick Triassic carbonate section in les rigides reminded everyone of the thick Triassic section in the Austro-Alpine nappes above and beyond the Pennine zone and in the Southern Alps, as in the Dolomite Alps. But Ellenberger's careful work on the Triassic carbonate sequence in la Vanoise in the French Alps, reported in his classic memoir on la Vanoise (1958), and comparisons of that sequence with the sequence in les rigides (Ellenberger, 1952; Genge, 1958; Botteron, 1961) have shown conclusively that les médianes are middle Pennine; the carbonate bank of les rigides corresponds to the Briançonnaise zone in France, les plastiques (approximately) to the Subbriançonnaise zone on the bank's external flank, and la nappe de la Brèche to the Pré-Piémontaise zone on its internal flank, all clearly Pennine. The latter two zones represent the basins on either side of the bank, which had partly oceanic floors, the Prépiémontaise actually being only the margin of the larger Piémont or Ligurian oceanic basin. The bank itself was built on a long sliver of continental crust detached (except perhaps far to the southwest) from its original, Variscan (European) source.[8] Moreover, sequences like those in the Briançonnaise and les Préalpes rigides are

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[8] Recently Stampfli (1993) has advanced the provocative idea that the Briançonnaise zone s.l. actually came from far to the west-southwest (present direction), a sliver from the European continental margin there that was brought to its present position outboard of the European margin as exposed in the Alpine external massifs by several hundred kilometers of left-handed strike-slip movement during the Cretaceous.

present in the Barrhorn series on the back of la nappe du Grand St. Bernard (Siviez-Mischabel nappe) in the middle Pennine zone of southwestern Switzerland (Ellenberger, 1952; Sartori, 1990) and in the Schamserdecken in eastern Switzerland. The Simmendecke (s.l.) probably includes non-metamorphic or at most anchimetamorphic equivalents of la nappe du Tsaté in the Swiss Pennine zone, of the upper Pennine schistes lustrés in France (calciscisti in Italy), and of the Plattadecke and associated units in southeastern Switzerland, or perhaps parts are truly Austro-Alpine.

The carbonate bank of les rigides, made of Triassic carbonate, evidently stood well above its flanking basins through Jurassic time, for it supplied blocks to the brecias in la nappe de la Brèche and the Pré-Piémontaise zone and also in the Subbriançonnaise zone, at least in France. The latest Jurassic Tithonian limestone encroached on it, but in Early Cretaceous time deposition ceased again. During Late Cretaceous time, it was gradually covered by the pelagic "couches rouges;" by the mid-Eocene it lay under the "flysch noir" seaway, perhaps as a low submarine bank.

In their present position, the Préalpes lie northwest of (external to) the anticlinorial external massifs of the Alps (Rodgers, 1995, p. 45 ff.), mainly opposite the saddle between the Aar massif and the Mont Blanc massif, but the ends of the main Prealpine mass overlap the ends of the two massifs and the central Swiss and French klippen lie in front of or even beyond them. At the saddle between the Pelvoux (P1) and Mercantour-Argentera massifs in southeastern France is the similar Ubaye-Embrunais klippe, but it consists almost entirely of flysch like that in the Simmendecke (s.l.); the rocks corresponding to the lower Prealpine nappes stayed behind, and indeed the klippe is cut off from its roots by an uplift of the Briançonnaise zone. Beyond the Argentera massif along the coast of northwestern Italy, la nappe du flysch à helminthoïdes has a similar position south of (external to) the Briançonnaise Savona axis.

The question arises how the extraordinary pile of nappes that now forms the Préalpes was assembled. May I suggest a scenario? The first step was to emplace the units of the Simmendecke, s.l., into the "flysch noir" basin (by diverticulation?), until they reached beyond the location of the former carbonate bank, now les rigides; perhaps the sparse sand in the "flysch noir" came from the uplifted flysch units. The Gurnigel and correlative flysch units (the first to move?) went even farther, beyond the basin of les plastiques. Next was the compression of the former bank and its flanking basins; first la nappe de la Brèche, with the internal part of the Simmendecke on its back, was emplaced over the bank, then the massive carbonate of les rigides punched up through and the marly sequence of les plastiques was folded, riding up over the Gurnigel flysch. As all these rocks moved forward, they covered the basin containing the Niesenflysch and the Zone Submédiane but forced the weak Ultrahelvetic rocks up and out until they slipped as a series of diverticulating gravity slides into the flysch basin of the Helvetic zone, which was being bent down by the weight of the approaching nappes. Soon the main Prealpine mass arrived over the margin of the Variscan cratonal rocks, the future external massifs, and by this time metamorphism and ductile deformation were affecting the rocks in the future Pennine zone (from which the Prealpine rocks had escaped though the comparable rocks in France, as in la Vanoise, had not), turning them into the schistes lustrés or Bündnerschiefer and the associated greenschists and marbles. At about this time also, the cover of the external massifs, caught beneath the Prealpine mass, became unglued (décollée) along the ubiquitous Triassic evaporites and rolled or slid forward to form the Helvetic nappes, involving the overlying Ultrahelvetic strata in its folds. About as metamorphism reached the external Pennine Niesenflysch, compression forced part of that out and into the back of the Prealpine mass (the rest remained behind as the schistes lustrés between the lower Pennine nappes—including the Lebendun conglomerates?). Then, as metamorphism reached the margin of the Variscan craton, parts of that margin too were forced upward and forward (and at a late stage backward) to form the external massifs; as they rose, the whole Prealpine mass slid forward (by gravity?) into its present position above the weak Ultrahelvetic cushion and beyond the firmer Helvetic folds and thrust sheets. I was standing with a French geologist friend amid les Préalpes du Chablais looking up at Mont Blanc to our south, and he said: "Mont Blanc shrugged its shoulders."

LE ARGILLE SCAGLIOSE: THE LIGURIDE ENSEMBLE OF THE NORTHERN APENNINES

The Apennines are the mountains that run the length of the Italian peninsula (fig. 5B, preceding p. 189), from Liguria (the province surrounding Genova), where they merge westward into the Western Alps, to Calabria and the Straits of Messina, beyond which the mountain axis continues across Sicily and on into North Africa to become the Maghrebide chain (mentioned above, p. 176). Strictly Alpine structures can be followed from southeastern France into northwestern Italy as far as Savona and a bit beyond; strictly Apennine structures from central Italy to the region east of Genova. The relatively lower mountains between Genova and Savona are chiefly dominated by a large massif of mafic and ultramafic rocks, the Voltri massif, which might be reckoned to either mountain range, for belts of ultramafic rock in each trend toward it.

A major distinction between the Alps and the Apennines in this region is their opposite vergence. In southeastern France and western Liguria the Alps verge southwest and south, toward Provence and the Gulf of Genova—in general toward the European plate—whereas the Apennines in Italy verge to the northeast or, as they approach Liguria, to the north, toward the Adriatic Sea and the Po Plain—in general toward the Adriatic or Apulian plate or subplate of the African plate (and in Sicily and North Africa southeast and south, frankly southward toward the African plate). Thus facies and tectonic units that are "external" in the Alps (leaving the Southern Alps out of account) are "internal" in the Apennines. The reasons for this striking change are still being debated; in any case they do not concern us here. In what follows, I shall deal mostly with the northern Apennines in Tuscany, in eastern Liguria, and across the mountain axis toward the Po Plain, from a line through Siena and Rimini northwest to the region of Genova (fig. 5A; see Merla, 1951; Elter, 1975a, b; 1980; Elter and Marroni, 1991).

"Basement" rocks are fairly scarce in the Apennines, in contrast to the Alps (basement is exposed in almost 50 percent of the Alpine area, including the Austrian Alps, according to von Raumer and Neubauer, 1993, p. 625). The largest mass is in Calabria at the south end of the Apennines; some of the largest masses within the northern Apennines are in the mountains called the Alpi Apuane in northwestern Tuscany between the cities of Lucca and Carrara (Conti and others, 1993); basement rocks also appear in Monte Pisano between Lucca and Pisa. The rocks here are Paleozoic quartzite and phyllite with minor volcanics and some carbonate toward the top; rare fossils indicate the presence of Silurian. The deformation of these rocks is ascribed to the Variscan orogeny but may have taken place in several phases during the later Paleozoic.

The unconformably overlying cover begins with basal conglomerate and quartzite ("Verrucano," named for La Verruca—the wart—in Monte Pisano), probably mainly fluviatile, originally assigned to the Permian but now considered Middle Triassic: these basal beds pass upward into Upper Triassic marine clastic strata. There follows half a kilometer or so of shallow-water carbonate rocks, largely dolostone below (associated with evaporite—mainly gypsum or anhydrite) and limestone above, and ranging from Upper Triassic to lower Lower Jurassic. Within the lower Jurassic however there is a major change: the limestone becomes cherty, its fossils indicate deeper water, and it gives way in the Upper Jurassic to radiolarian chert and still more cherty limestone, ranging in thickness from 20 to 150 m but clearly representing a long period of time, extending into the Lower Cretaceous. Equally thin for the time involved are the following strata—limy mudstone, muddy limestone, and some layers of purer limestone (pelagic, not shallow-water)—which extend to the Eocene or lower Oligocene. The Lower Cretaceous strata are mainly gray, though some of the purer, but still clayey, limestone weathers white ("maiolica" or "biancone"); the Upper Cretaceous and Lower Tertiary are more variegated—green, gray, pink, and red ("scaglia;" compare the "couches rouges" of the Alps, p. 186)—and are full of planktonic foraminifera (which only became abundant organisms during the Cretaceous). The total thickness of this fine-grained sequence is around 1½ km.

This long period of quiet, slow, open-ocean sedimentation ended abruptly in the later Oligocene (not until the Miocene to the northeast) with the appearance of a sequence, up to 2 km thick (in other words, thicker than the whole sequence below down to the Triassic), of graded sandstone beds alternating with shale—the macigno, a typical flysch. Indeed it was his careful study of the macigno that led Carlo Migliorini to the concept that the graded beds in flysch are deposited by oceanic turbidity currents. Having reached this conclusion, he discovered (during the International Geological Congress in London in 1948) that Philip Kuenen had reached the same conclusion from his flume experiments in the backyard of the Geological Institute at Groningen in the Netherlands; the result was their epoch-making article (Kuenen and Migliorini, 1950) with which the modern study of deep-sea sedimentation begins.

The sand (and indeed gravel) grains in the macigno are mostly quartz and feldspar (especially K-feldspar and albite), implying a granitic or gneissic source area; fragments clearly coming from the underlying stratigraphic sequence, such as the carbonate or the radiolarian chert, are quite lacking. Intercalated in the upper layers of the scaglia and the lower layers of the macigno are beds composed of Eocene or even Oligocene nummulites—"brecciole"—now understood to be resedimented, turbidity-current deposits of calcareous rather than quartzofeldspathic sand, but in any case not derived from the underlying strata.

This whole stratigraphic sequence, from Triassic to mid-Tertiary, is called the Tuscan facies or sequence; as it consists of a series of well defined and quite distinctive units, its structure could be readily worked out. It crops out in several rather irregular anticlinorial belts, the most prominent extending from the Alpi Apuane southeastward past Siena. Within the Alpi Apuane it was recognized fairly early that the sequence is duplicated; despite some controversy, the duplication is now explained by fairly large-scale thrusting, the largest and uppermost thrust sheet being called the Tuscan nappe. (The lowest sequence is mildly metamorphic, the famous Carrara marble being its metamorphosed basal Jurassic limestone; it involves the basement and is commonly called autochthonous, but whether it is truly so is another question.)

The Oligocene to basal Miocene macigno seems to wedge out eastward and northeastward; beyond a limit somewhere near the present crest of the Apennines, the Oligocene is represented by the same facies as the underlying Eocene (but gray only—scaglia cinerea). Here, however, the Miocene appears in a turbidite facies ("marnoso-arenacea") much like the macigno. This region has been distinguished from the Tuscan "domain" and called the Umbrian "domain," though the only significant stratigraphic difference is the age of its flysch. Clearly the arrival of the flysch facies was diachronous from southwest to northeast, though perhaps the forward movement was irregular and episodic.

Above or beside the macigno and its Miocene relative, and also in places above or beside lower units of the Tuscan facies, are other sedimentary rocks of several kinds—mudstone, shale, siltstone, sandstone (much of it flysch-like), calcareous flysch, and also considerable bodies of altered mafic volcanics and ultramafic rocks (now largely greenstone and serpentinite) and rare blocks of granitic rock. In contrast to the well characterized Tuscan stratigraphy, the stratigraphy of these rocks proved very difficult to decipher, even though Cretaceous and lower Tertiary fossils date some of the rock types. This group of rocks, clearly in large part coeval with the Tuscan sequence, is called the

Ligurian facies or ensemble. Rocks of this facies are present across the entire width of the northern Apennines, from the Tyrrhenian coast of Tuscany and eastern Liguria to the Adriatic coast and the Po Plain.

Prominent and widespread among the Ligurian rock types in Tuscany and to the northeast is one long called "argille scagliose," scaly clays, practically characterized by its tendency to slip on any inclined land surface. The Italians build excellent roads, as did the Romans before them; when one is driving on a highway in the northern Apennines and the car begins to lurch, one can be virtually sure that one has entered an outcrop area of the argille scagliose. Good outcrops of this rock are difficult to find; mostly one sees messy roadbank or streambank exposures, partly covered by soil, turf, or bushes slid from above, and one can never be sure whether the exposure itself has or has not slipped downhill. The other rock types of the Ligurian facies form better outcrops and can sometimes be mapped over considerable areas, but in Tuscany they are generally separated from one another by areas of the argille scagliose, so that their mutual relations were difficult to establish there. They appear indeed to be fragments or large blocks surrounded by argille scagliose, and, like that material, they tend to slide downhill. Thus much of the Republic of San Marino at the northeast foot of the Apennines southwest of Rimini consists of neoautochthonous, "epi-Ligurian" strata (see below, p. 196) resting on argille scagliose, and the whole mass is apparently sliding gently down toward the Adriatic.

The scaly clay consists essentially of small slivers of clay, more or less the size of seeds (from grass seeds to watermelon seeds), generally with shiny, seemingly slickensided surfaces. Where exposures permit, one sees that these slivers are crudely aligned along subparallel surfaces; the alignment is not like that of ordinary cleavage or schistosity (it resembles more that of "fish-scale schist," though the scales are smaller) but rather of an intricately anastomosing fabric of tiny slip planes. The subparallel alignment commonly shows bumps and bends, rarely describable as folds; a somewhat better analogy would be that of the foam on a polluted river (especially just below a tannery or a paper-mill), pulled out and twisted by the currents and eddies of the river. Very common in the scaly clay are fragments of other, tougher rocks—notably of dirty siltstone or graywacke and of limestone—and the alignment "flows" around these fragments, which can be of all sizes from that of peanuts on upward. Despite the ubiquitous slickensided surfaces of the clay slivers, metamorphism is lacking or at most very low grade; the parent "rock" is, or was, sedimentary, presumably mud gorged with water.

The other rock types in the Ligurian facies occur either, especially in Tuscany and to the northeast, as fragments in the argille scagliose (where they seem to have no upward size limit) or, especially in Liguria, as more coherent masses or sequences, forming several superposed nappes or thrust sheets (all lying above the Tuscan facies and its nappes). Even in the larger blocks in the argille scagliose (tens of meters to tens of kilometers across), the sedimentary rocks show perfectly recognizable bedding and indeed consistent sequences of strata. The margins of some fragments, however, particularly those in which some of the beds are themselves shale or mudstone, appear frayed and grade from well bedded to fragmented and on into the typical scaly clay with small fragments.

Some of the fragments in the argille scagliose can be identified with formations of the Tuscan facies, but most cannot. Most striking of the latter are the mafic and ultramafic rocks, already recognized as ophiolites by Steinmann (1907). Where the masses are large enough (they range up to 10 km), even a sort of ophiolite "stratigraphy" can be recognized—ultramafics, "eufotidi" (= saussuritized gabbro), basalt (including pillow lava), and radiolarian chert. (The rather rare "granitic" fragments reported may be plagiogranite or trondhjemite of the kind not uncommonly associated with ophiolites, or they may be of continental origin.) A significant fact about the ophiolitic masses is that the fairly large ones lie for the most part fairly near the Tyrrhenian coast; away from that coast the average size becomes smaller, and, farther to the northeast, the number also decreases, though not to zero (Merla, 1951, Tavola 1).

Another major component of the Ligurian facies is arenaceous turbidite (fine-grained—"pietraforte"—or coarse-grained—"arenarie superiore"), Upper Cretaceous to Paleocene and coeval with much of the scaglia in the Tuscan facies. Most of the sandstone in these turbidities is quartzo-feldspathic, but in the lower part, especially just northeast of the main bodies of ultramafics, some beds are largely "ophiolitic" débris, partly as graded turbidites but partly as coarse breccias or olistostromes—sedimentary mélanges. In other words, the ophiolite was already being uplifted and eroded in Late Cretaceous time.

Another major rock type is calcareous flysch, fine-grained limestone turbidites in which quartz sand is confined to the basal centimeters of the graded beds; these strata range from middle Upper Cretaceous to Eocene (the latter only to the northeast). The Cretaceous part is characterized by helminthoids and is coeval with the flysch à helminthoïdes of the Alps (see p. 188, 190); the Tertiary part lacks them, but otherwise is not very different.

In Tuscany all these rock types are prominent as blocks of all sizes in the argille scagliose, but in Liguria they tend to form separate thrust sheets. In central Liguria, east of Genova, a major sheet of the calcareous turbidite, the Monte Antola nappe, had already been thrust *southwestward* over sheets made of the arenaceous turbidite and the ophiolite in late Eocene or Oligocene time, before the whole mass of rocks of Ligurian facies began to move *northeastward* over the Tuscan facies during the Miocene; thus the earlier thrusting had an "Alpine" vergence, and only the later movement was "Apennine."

As noted above, the ophiolitic rocks and the associated radiolarian chert in the Ligurian facies are Upper Jurassic. Lower Cretaceous is mainly represented by shale, in which very fine-grained limestone ("palombini") appears as lenses or layers or, near the base, as thicker units;

some of this limestone is not unlike that of the same age in the Tuscan facies ("maiolica"). Toward the top of the Lower Cretaceous appear the first turbiditic sandstones.

Forming still another component of the Ligurian ensemble are the "epi-Ligurian" basins, bodies of mainly Lower Tertiary clastic strata (younger to the northeast) that overlap, unconformably, the various Cretaceous rocks of the facies described above but that were later emplaced with the rest of the Ligurian facies over the Tuscan facies. Evidently deformation began in the *patrie* of the Ligurian facies in Cretaceous time, as shown by the "ophiolitic" turbidites mentioned above, and continued, perhaps in pulses, through the Late Cretaceous and Early Tertiary until the final Miocene pulse, the only one that involved the Tuscan facies as well.

Another striking fact is that, locally, typical argille scagliose is recorded forming beds that lie *between* graded beds in the uppermost (basal Miocene) part of the macigno (and also in the marnoso-arenacea), indicating that the Ligurian facies was already being emplaced over the typical Tuscan facies before deposition of the latter had ceased.

Tuscan facies and Ligurian facies alike are overlapped by late Tertiary, post-orogenic deposits, but the overlap facies too is clearly diachronous. In Tuscany and generally on the Tyrrhenian side of the peninsula, the first deposits are middle or upper Miocene, but on the northeast side they are uppermost Miocene or even Pliocene. Furthermore, in the subsurface of the Po plain north of the northern Apennines drilling has encountered argille scagliose, including fragments of other rocks, with Pliocene above *and below,* in the same way that the Prérif nappe is interbedded in the upper Miocene section in northern Morocco. Judging by seismic activity and by deformation of Pleistocene and even Recent alluvial cones and terraces along the northeast foot of the Apennines, deformation is still going on there.

If now one tries to reconstruct a consistent history and paleogeography for the Ligurian facies out of all its rocks, one must first omit the fragments of the Tuscan facies in the argille scagliose, which presumably found their way in from below during the Miocene, and one must also keep in mind that several stratigraphic sequences are represented. The base would be the ophiolites, representing oceanic crust and upper mantle on which much of the rest was deposited, beginning with the radiolarian chert; judging by the age of the chert, the ocean floor would be Late Jurassic. The Lower Cretaceous is represented by shale and fine-grained, sometimes cherty, pelagic limestone, evidently deposited in that oceanic basin far from any sources of coarse sediment. The Upper Cretaceous certainly includes both the arenaceous and the calcareous flysch, though probably they formed in different parts of the basin, separated, at least in later Cretaceous time, by a ridge of the ocean floor. The Cretaceous arenaceous turbidite has a good deal in common with the Oligocene macigno in the Tuscan facies; perhaps arenaceous flysch progressed as a diachronous facies all the way from the most internal belts on the southwest in the mid-Cretaceous to the most external belts on the northeast in the Miocene, but in the intermediate belts the main deposit was the calcareous flysch, and the two bodies of quartzo-feldspathic flysch may well have had different source areas. As for the argille scagliose, it contains fossils ranging from Lower Cretaceous to Oligocene, but one cannot tell which of these fossils are fragments within it and hence irrelevant to its age. A possible hypothesis is that the bulk of the argille scagliose represents the Lower Cretaceous part of the Ligurian sequence (or sequences), and that, when that sequence was expelled from its *patrie* to the southwest of the Tuscan sequence, its Lower Cretaceous part was in some areas still so gorged with water that it acted as a massive slurry in which blocks of all the other parts became chaotically imbedded. On the other hand, some or even a major part of its clay might have been contributed from clayey interbeds in the various flysch units, or from younger, Tertiary, units not represented among the fragments. In any case, olistostromes or sedimentary mélanges began to form in Cretaceous time, were especially prominent in the mid-Tertiary, and may still be forming today.

Just as in the Prérif, the nappe theory so successful in the Alps at the beginning of this century was imported into Italy, and the rocks of the Ligurian facies were considered to form a great Liguride nappe overriding the Tuscan facies and its nappes across the entire width of the peninsula. But the map relations of this enormous nappe remained obscure, and an anti-nappist reaction set in (as in many other countries, though not in the Swiss and French Alps); the relation of the Ligurian rocks to the Tuscan facies was explained by local tectonics, by complicated paleogeography, by diapirism, or simply by ignoring the inconvenient fossils and postulating stratigraphic superposition. During the late '20s and '30s another concept appeared, that of gravity sliding. Applied in Italy at first only to local overlaps (Bonarelli, 1929), it was gradually generalized to larger and larger areas and finally used to explain the whole of the "Liguride nappe," the argille scagliose being considered the matrix of one or more giant, compound olistostromes. But sliding requires not only a low area where one now finds the slid masses but also an uplifted area to provide the gravitational potential for the sliding. A first attempt to postulate a single uplift in the present area of the Tyrrhenian Sea (where Corsica and Sardinia are inconveniently close to the Italian peninsula) failed because the uplift would have had to be impossibly high to explain sliding as far as the Adriatic coast, and no sign of such a giant uplift remains on the Tyrrhenian side of the peninsula. More plausible was the idea of a series of parallel but diachronous uplifts, each pushing the sliding mass northeastward to where the next uplift would appear; this idea was carefully worked out by Migliorini (1948) and Merla (1951, p. 181 ff.), and in Tuscany the existing anticlinoria of the Tuscan facies, such as the Alpi Apuane, were identified as some of the uplifts.

As noted above, the argille scagliose is particularly chaotic in Tuscany, but as the rocks of the Ligurian facies were followed northwestward into eastern Liguria, larger and larger coherent packages of one or another of the major rock groups were found to form tectonic units, superposed one over the other in a consistent order. Concepts of nappes pushed by compressive forces were therefore reintroduced, but the rôle of gravity was not denied; thus a sort of eclectic theory has been worked out (Elter, 1980; Elter and Marroni, 1991). Moreover the fixism of the anti-nappists and of the early proponents of gravity sliding has given way to the mobilism inherent in the theory of plate tectonics.

Recent studies of mesoscopic and microscopic structure in the argille scagliose (Bettelli and Papini, 1987; Pini, 1991; and other articles in the same volumes) have shown that "scaly structure" of olistostromal origin can be distinguished from that of tectonic origin, the latter being related not to gravity slides but to thrusting in accretionary wedges (indeed, such structure has been reported, though only on a small scale, in deep-sea drill holes at the toes of present-day accretionary wedges; Moore and others, 1986). At least some of these studies suggest, moreover, the presence in the argille scagliose of olistostromal deposits that have then been tectonized—that is, gravity slides incorporated into an accretionary wedge—or, conversely, of tectonic argille scagliose melting into the olistostromal variety.

One might suggest however that, in reaction to the earlier overemphasis on gravity as an explanation, the pendulum today has swung to an overemphasis on compressional tectonics. Sedimentation and compressional tectonics do not operate separately, as they were supposed to do in the older geosynclinal syntheses; they go on together, with varying relations of dominance, each constantly though irregularly influencing the other.

THE "KEVAN GRAVITY NAPPE" OF SOUTHEASTERN TURKEY

In southeastern Turkey (Rigo de Righi and Cortesini, 1964; Perincek, 1979; Fontaine and others, 1989), the Arabian shield is bounded on the north by the Taurus Mountains, a northwestern continuation of the Zagros Range (Za) of Iran and one of the links in the southern margin of the Alpine-Himalayan orogenic belt; the major compressive deformation of the Taurus was late Miocene (and Pliocene?), but large-scale strike-slip movement is still going on. Over much of the Arabian shield (including this part of Turkey), Precambrian basement is covered by nearly flat-lying sedimentary strata, beginning with Cambrian; to the south the cover is relatively thin and incomplete, and to the north, even in the thicker but still autochthonous sequence in the immediate foothills of the Taurus, major disconformities separate Devonian from Permian, Triassic from Lower Cretaceous, and (within the Upper Cretaceous) Cenomanian or Turonian from middle or upper Senonian. The lower part of the sequence is largely clastic, but upward, beginning tentatively in the Permian and definitively in the Lower Cretaceous, carbonate becomes dominant, partly as reefs and locally associated with layers of evaporite. Beginning in Late Cretaceous (late Senonian) time, part of the northern margin of the platform subsided and received first dark shaly and cherty limestone, then flysch (partly calcareous, especially below), clearly in response to an important orogenic pulse in the Taurus orogenic belt to the north; farther south, however, deposition of reefy limestone continued. Upward the flysch passes over into molasse-like sediments—conglomerate and redbeds—of latest Cretaceous age; to the north they lie on the flysch with angular unconformity, but elsewhere they appear conformable. Farther south the molasse too grades laterally into marine shale surrounding reefs (some of the reefs may have grown on the crests of folds that were forming in the sedimentary cover at that time). In the Eocene, carbonate (again accompanied by evaporite) returned to the region, but in Miocene time the northern margin again subsided and received flysch, then molasse, from the newly deformed orogenic belt, whereas well to the south carbonate was gradually replaced by non-marine clastics. All these sedimentary rocks were then folded, sharply to the north where reverse faults accompany the anticlines (both verge south), more gently farther south. Although this last and strongest folding involves the Miocene strata, there was probably earlier folding, especially in the latest Cretaceous.

In a belt along the northern margin of the folded zone, inserted in this stratigraphic sequence about at the contact between the uppermost Cretaceous flysch and molasse, is an exotic unit, called the Kevan gravity nappe and Besni olistostrome by Rigo de Righi and Cortesini (1964, p. 1922-1923) and characterized by its chaotic structure. The rocks in this unit fall into three groups. One is variegated shale (Upper Jurassic? to Upper Cretaceous), commonly with a scaly texture and locally siliceous with lenses of chert and cherty limestone; a second is Mesozoic limestone, consisting of half a kilometer mainly of poorly dated dolostone—Triassic? Lower Jurassic?—followed by deeper water limestone, then shale with carbonate turbidites—Middle Jurassic to Lower Cretaceous; the third is altered mafic and ultramafic rock, including pillow lava, associated with Upper Jurassic radiolarian chert and cherty limestone. None of these rock types is present in the autochthonous sequence, and a large part of the age span of each group is represented there by the Triassic-Lower Cretaceous disconformity, whereas many of them, especially the mafic and ultramafic rocks, crop out extensively within the Taurus Mountains to the north.

The exotic unit can be mapped along the outcrop as a formation up to 600 m thick, taking its regular, predictable place in the stratigraphic sequence; it has also been penetrated by wells, one of which went through it for 2 km before reaching the underlying flysch and lower units. Being already part of the sequence, the exotic unit was folded with the rest of the strata by the Miocene deformation. To the north of the belt in which the unit seems to be intercalated in the sequence, it is unconformably overlain by the latest Cretaceous and early Tertiary molasse conglomerate, which contains fragments of its exotic rocks, or by higher units. To the south it disappears from the sequence along a reasonably sharp line, beyond which the Upper Cretaceous flysch below simply passes upward into the molasse or its marine equivalent.

According to Rigo de Righi and Cortesini (1964, p. 1923), the scaly shale acts as a matrix for the other rocks, which occur within it as blocks, slices, or larger masses (up to 10 km for the limestone, even more for the mafic-ultramafic rocks); they therefore interpreted the intercalation of the exotic unit into the otherwise normal stratigraphic sequence (as in the Prérif) as a gravity slide or flow originating in the orogenic belt to the north, whose latest Cretaceous uplift is also recorded by the flysch and molasse sediments that accompanied the flow but extended beyond it. (Unlike the Prérif, however, the flow would have been separated from the final climax in the adjacent orogenic belt by tens of millions of years.) On the other hand, Fontaine and others (1989), considering especially the northern part of the belt, where the uppermost Cretaceous molasse rests unconformably on both the flysch and the exotic rock types, interpreted the structure in terms of three separate conventional thrust sheets, though agreeing that the limestone appears as relatively sharply bounded masses within both the scaly shale and the mafic-ultramafic group. They further showed that the limestone and scaly shale units can be interpreted as part of the transition from the incomplete, autochthonous sequence on the margin of the shield toward the oceanic realm represented by the mafic and ultramafic rocks and the associated sediments.

During the Miocene the rocks of the Taurus Mountains—not only those that are like the three groups in the exotic unit but also Tertiary sedimentary and volcanic rocks—were thrust southward over the foothills rocks, especially over the Miocene flysch; they were displaced at least 20 km, probably considerably more, and to the east they completely cover the folded belt. Along parts of the thrust front, however, the rocks directly north of the thrust are not those rocks but older gneiss and granite or "basement" (Paleozoic?) in the Bitlis (Bt) and Pütürge uplifts, which appear to be "external massifs" like those in the Alps and elsewhere (Rodgers, 1995), probably marginal portions of the Arabian shield that rose late in the Miocene orogeny between the foothills and the internal Taurus (no fragments of these rocks are found, however, in the exotic unit).

THE TACONIC KLIPPEN OF THE NORTHERN APPALACHIANS

The type Taconic klippe.—The original Taconic Mountains (fig. 6A, between p. 204 and 205) are the range, 75 km long, along the border between Massachusetts and New York, but the name has also been applied to mountains that extend a little south into northwesternmost Connecticut and 115 km north along the New York-Vermont border and into western Vermont. The Taconic region also includes Mount Greylock in northwestern Massachusetts and extends westward across lower hills to within sight of the Hudson River.

The severely deformed and variably metamorphosed rocks of the Taconic region were the center of a bitter controversy from 1840 through the rest of the 19th century, but I shall not consider that controversy here; it has been worked over many times, and I too have discussed it more than once, along with its 20th-century sequel (Rodgers, 1970, p. 75 ff., 1989, 1997). I cannot however avoid the sequel controversy, to which I have been a party, but I shall try to set out the facts fairly before entering on the polemics.

Along and near Lake Champlain, which forms the northern half of the boundary between Vermont and New York, a characteristic Appalachian Cambro-Ordovician sequence crops out—sandstone at the base, a principally carbonate succession in the middle (mainly dolostone to the west, at least half limestone to the east), and shale and eventually graywacke above; in what follows I refer to it as the carbonate sequence. To the west, where it laps up on the Precambrian (Grenville) basement of the Adirondack Mountains (last metamorphism about 1000 Ma), this sequence is rather thin (up to 700 m), extends only from the Upper Cambrian into the Middle Ordovician, and contains several disconformities. Here it is deformed only by or close to a system of large normal faults (the ones mentioned parenthetically in Rodgers, 1987, p. 671). Eastward across the lake, however, it enters a typical if rather narrow fold-and-thrust belt (Ch; Rodgers, 1991, p. 864); it becomes thicker (1½-3 km), begins with Lower Cambrian quartzite (and, to the east, with underlying, possibly latest Precambrian graywacke), and is more nearly complete. It is cut by several fairly large thrust faults, but the major structure is the highly imbricated Middlebury synclinorium in which Middle Ordovician slate is preserved, especially at the north and south ends of the belt where the synclinorial axis plunges respectively north and south. To the east the complementary anticlinorium forms the Green Mountains (GM; Rodgers, 1995, p. 464); reworked Adirondack basement crops out in its core to the south (beginning only a little north of the north end of the Taconic Mountains, s.l.). The mutual flank of synclinorium and anticlinorium is cut by large but not everywhere continuous thrust faults. Metamorphism begins near the axis of the synclinorium and increases eastward; some of the carbonate rocks on its east flank have become commercial marble. Slaty cleavage is common in the synclinorium and also to the west in shale and shaly limestone; it can even be found in otherwise undeformed, flat-lying shale west of the westernmost presently exposed folds and thrusts.

The carbonate rocks crop out southward along each flank of the south-plunging Middlebury synclinorium; the outcrop belt on the west flank turns southwest along the southeast flank of the Adirondacks (though broken by the normal faults), whereas that on the east flank can be followed south, with only minor interruptions and a good deal of anastomosing, through southwestern Vermont, westernmost Massachusetts, and northwestern Connecticut, and back into the eastern edge of New York State. This belt forms the "marble valley" on the west side of the Green Mountains and Berkshire ("external") massifs and then ramifies around other Precambrian massifs farther south (all these massifs belong to the Green sector of the Blue-Green-Long axis of the Appalachians; Rodgers, 1995, p. 464 ff.). Metamorphism here is in the amphibolite facies except at the two ends of the belt—in west-central Vermont and the western belts in southeastern New York—where it falls off and fossils can be found. Many recent studies of the physical stratigraphy in this eastern belt show that a consistent sequence of units can be followed throughout, and the fossils at the two ends confirm that it extends from Lower Cambrian to Middle Ordovician.

The Taconic region lies in the southern continuation of the Middlebury synclinorium, between these two carbonate belts. In it is exposed a great mass of mainly slaty rocks that range from low-grade slate on the west (quarried extensively in parts of Vermont and New York) to amphibolite-grade schist on the east. As the black shale at the top of the carbonate sequence is known by fossils to be Middle Ordovician, the overlying slaty rocks should obviously be Middle Ordovician or younger. But although fossils are not easy to find in these rocks, they do occur; Lower Cambrian trilobites were found as early as 1844 (Emmons, 1844, though their age was not established until 1860—Barrande, 1861), and as work progressed more and more fossils have been discovered. We know now that the Taconic rocks form a stratigraphic sequence, the Taconic sequence, covering exactly the same time-span as the carbonate sequence—Early Cambrian to Middle Ordovician.

Deciphering the stratigraphic sequence in these highly deformed rocks was very difficult, but it was accomplished by decades of detailed mapping and careful attention to the fossils as they were gradually discovered; the pioneers were Dale (1899, 1904) and Ruedemann (1901; Cushing and Ruedemann, 1914, p. 66-99). At the base are entirely unfossiliferous graywacke, siltstone, and even conglomerate (rather like the graywacke at the base of the thickest section of the carbonate sequence, on the west flank of the Green Mountains anticlinorium), but most of the strata are slate or silty slate (to the east, schist), with conspicuous but minor chert in the Ordovician, thin units of quartzite or calcareous sandstone, especially in the Upper Cambrian, and beds of limestone-conglomerate here and there throughout, though mostly along the west margin of the Taconic region. At the top, graywacke reappears in abundance (*before* the cessation of carbonate deposition in the carbonate sequence). Once the stratigraphy was clear, the structure could be worked out (for example, by Zen, 1961); it is dominated by large mainly west-vergent isoclinal folds (they are recumbent near the north end in the core of the synclinorium) cut in many places by thrust faults.

The rock types in the carbonate and Taconic sequences are in strong contrast, and this contrast is underlined by the fossils. The carbonate strata of the carbonate sequence (and also the underlying sandstone) show the marks of shallow-water deposition—cross-bedding (even in the carbonate), edge-wise conglomerate—and the fossils are "shelly"—

stromatolites, shallow-water trilobites, gastropods, and cephalopods (when they appeared). Clearly they record a great carbonate platform or bank along the east side of the North American craton. Only the graptolite-bearing black shale and the overlying graywacke at the top of the sequence (both Middle Ordovician) indicate deeper water; evidently the platform had begun to founder. The Taconic strata on the other hand record a basin, starved except at the base and top; they show graded bedding (distal in the silty slate, proximal in the overlying graywacke), and the quartz-sandstone layers appear to represent sand-flows. The fossils are mainly planktonic (Ruedemann, 1934)—conchostracans, conularids, and above all graptolites in the Ordovician; even the trilobites belong to a different facies than those on the platform. Finally, a few studies (Ross, 1949) have shown that the fragments in the limestone-conglomerate beds along the western margin of the Taconic region came from the carbonate sequence, as indicated by both rock-types and fossils; thus the western part of the Taconic sequence was deposited fairly close to the eastern edge of the carbonate bank.

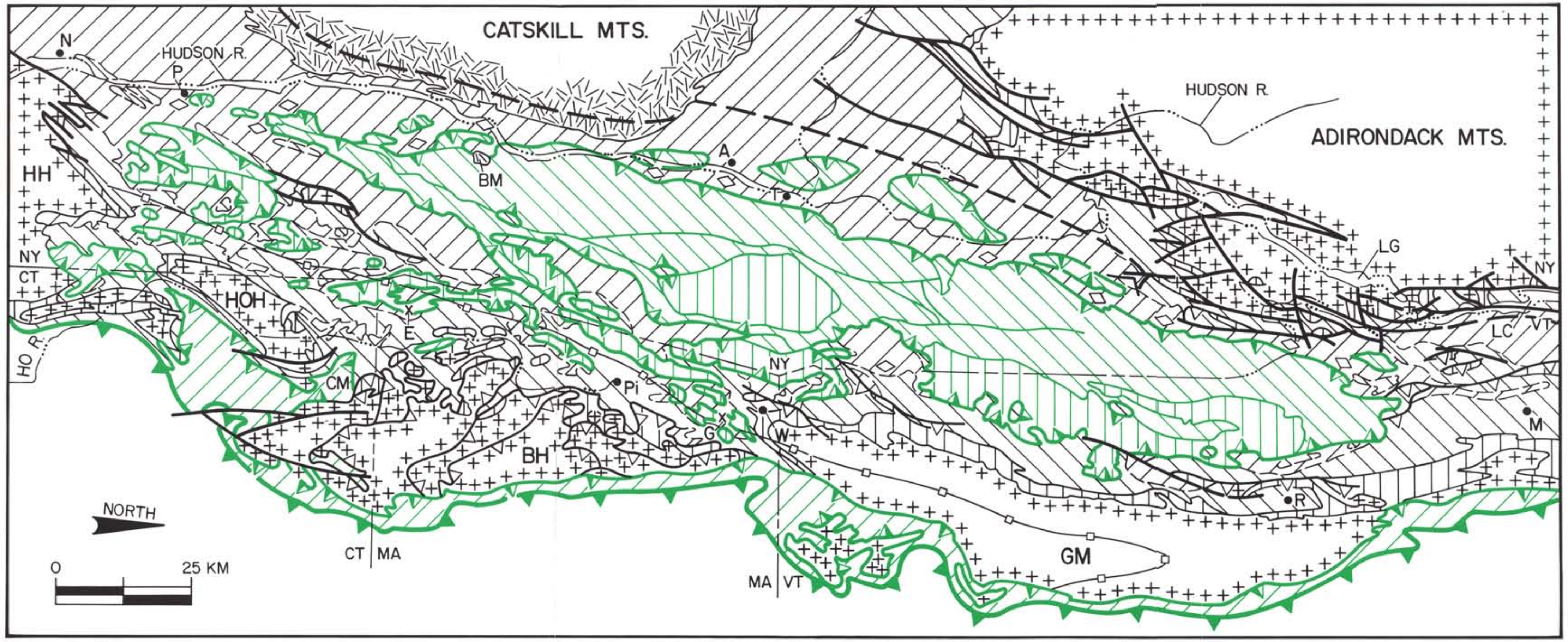
As these relations between the two sequences became clear, several hypotheses were suggested to explain them. The simple hypothesis that the Taconic sequence overlies the carbonate sequence stratigraphically foundered as soon as the significance of the Taconic fossils was understood; attempts to revive it for the unfossiliferous mica schists to the east have also failed, for stratigraphic units can be traced into the higher grade rocks. Likewise an attempt to deny the exact correlation of individual carbonate and slate units and to interleave them into a single stratigraphic sequence by postulating multiple disconformities (Bucher, 1957) failed as more and more fossils were discovered, and the correlations were demonstrated. Dale (1899, p. 295-297) seems to have held that the slate sequence was deposited in a sort of cul-de-sac surrounded by the carbonates; this hypothesis was carefully worked out by Lochman (1956, p. 362 ff., plate 10). Its advantage was to permit a structurally simple autochthonous explanation of the regional geology, but at the cost of great stratigraphic and paleogeographic complexity.

Ruedemann (1909, p. 189-192) very early suggested the contrasting allochthonous hypothesis that the Taconic sequence is structurally superposed on the carbonate sequence as a great thrust sheet, now a klippe nested in the synclinorium, although at that time too little was known to determine whence the thrust sheet came. For most of this century, as work proceeded, these last two hypotheses contested the field, but by now most (but not all) of those familiar with the region have accepted the allochthonous hypothesis.

The allochthonous hypothesis had to face several difficult problems, however. First was the question of the root of the thrust sheet, the *patrie* of the basinal Taconic sequence. It was sought on the eastern side of the Green Mountains anticlinorium, but the Paleozoic section there, of still another (eugeosynclinal) facies, seemed to be continuous. It was sought in the thrust faults along the western front of that anticlinorium, but the ramifications of the eastern carbonate belt in between the various massifs farther south made this solution too arbitrary and *ad hoc*. It was sought on top of the anticlinoria, from which the Taconic sequence would have slid by gravity into its present position (White *in* Cady, 1945, p. 570, 578), but the anticlinoria are too discontinuous, even though it has become clear that the Taconic klippe is not monolithic but is made up of several separate slices or thrust sheets.

Finally it was found that the Paleozoic sequence east of the anticlinoria is by no means continuous but is broken by many thrust faults, one of which separates the western sequences from the eastern one (the eugeosynclinal facies, which contains ultramafic bodies near its western margin). This major fault was first recognized in western Connecticut by Agar (1927) and Cameron (1951) as the boundary between two schist units with quite different histories (there it is called, informally, "Cameron's line"), and it has now been traced northward across Massachusetts (the Whitcomb Summit thrust) and far into Vermont (see fig. 6A). Indeed it probably plays the same rôle here that the Pennine thrust front plays in the Alps.

Another problem was the great difficulty in determining the limits of the allochthonous mass or masses. In many areas no clear boundary could be found between dated Middle Ordovician black slate at the top of the carbonate sequence and overlying Cambrian black slate (locally inverted!) of the Taconic sequence. Even where a sharp boundary, a thrust fault, can be traced along the western edge of the main Taconic slate mass, nevertheless other large masses of slate west of that boundary contain fossils too old to belong to the slate at the top of the carbonate sequence. Furthermore the sharp boundary in question, though traceable for about 200 km from near the north end of the klippe south beyond Albany, NY, seemed to dissolve farther south into several lines; for a while, the hypothesis was entertained that the "klippe" was allochthonous at its north end but rooted at its south end! Visiting the Prérif in 1952 suggested to me that the vague boundary could be understood if the Taconic mass arrived as poorly lithified muddy material that slipped during the Middle Ordovician into the depositional basin over the carbonate sequence, the black mud that was there accumulating being itself alimented by slacking and erosion of the Cambrian mud with which it came in contact. Several of us, notably Zen (1961, p. 211 ff.), Berry (1962, p. 713), Bird (1963, p. 17-19), and Potter (1963, p. 62, also 45-47), began to find evidence of olistostromal deposits ("blocks-in-shale," "wildflysch breccia") in the "autochthonous" strata close to the sharper boundaries, deposits in which blocks of Taconic slate (and in several areas also blocks of the carbonate sequence) are embedded in a matrix of the autochthonous slate, both blocks and matrix commonly carrying fossils (especially graptolites). Such deposits have now been demonstrated at many localities along the entire western front of the main Taconic klippe and have also been found in reentrants or half-windows on its eastern side (they are indicated by open diamonds on fig. 6A). The remaining



A.

Fig. 6(A) Schematic tectonic map of Tàconic klippen in Taconic region of New York, Vermont, Massachusetts, and Connecticut.

Black line with double dashes: state line

Black line with three dots: river or lake-shore

Nearly straight heavy black line: normal fault (age uncertain: Ordovician? Triassic?)

Medium broad-dashed line: western limit of Appalachian deformation

Random black dashes: unconformably overlying Devonian and Upper Silurian strata

Heavy green line with filled triangles—western boundary of "eugeosynclinal" sequence—Whitcomb Summit thrust or "Cameron's line"

Heavy green line with half-filled triangles—Taconic contact, border between rocks of Taconic sequence in klippen and shale or slate at top of carbonate sequence

Light green line between areas of green patterns—thrust boundary within Taconic klippen

Green lines tilted to right: Hoosic, Canaan Mountain, or Manhattan schist—higher grade equivalent of Taconic sequence

Green vertical lines: "High Taconic" thrust sheets

Green lines tilted to left: main body of Taconic sequence (Middle Ordovician to Lower Cambrian)

Thin black line with squares: garnet isograd (garnet is to east or southeast)

Black line with open triangles: thrust fault within carbonate sequence (not all shown)

Black open diamond: outcrop area of "wildflysch breccia," "blocks-in-shale," et cetera, in shale at top of carbonate sequence

Black lines tilted to right: shale or slate at top of carbonate sequence (Middle Ordovician)

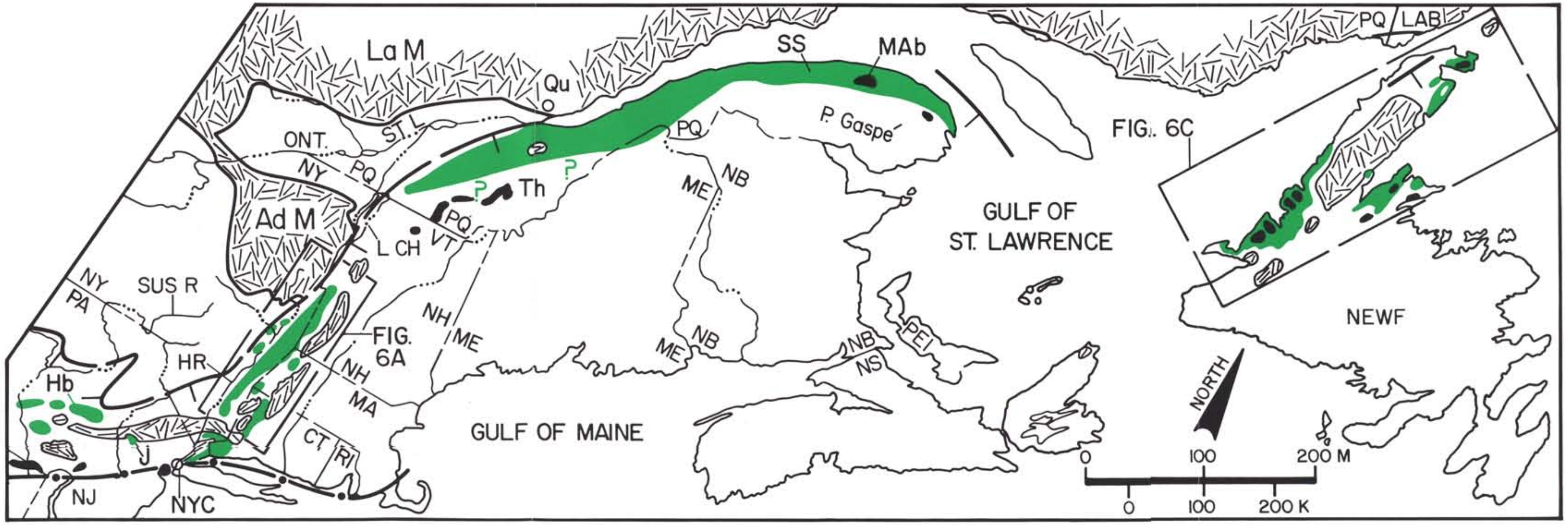
Black lines tilted to left: carbonate rock of carbonate sequence (Middle Ordovician to Lower Cambrian)

Vertical black lines: quartzite at base of carbonate sequence, where separated (Lower Cambrian within Appalachian deformed belt, Upper Cambrian outside it)

Black crosses: Precambrian (Grenville) basement

Letters:

A—Albany, New York
BH—Berkshire Highlands
BM—Becraft Mountain
CM—Canaan Mountain
E—Mt. Everett
G—(Mt.) Greylock
GM—Green Mountains
HH—Hudson Highlands
HOH—Housatonic Highlands
HO R—Housatonic River
LC—Lake Champlain
LG—Lake George
M—Middlebury, Vermont
N—Newburgh, New York
P—Poughkeepsie, New York
Pi—Pittsfield, Massachusetts
R—Rutland, Vermont
T—Troy, New York
W—Williamstown, Massachusetts



B.

Fig. 6(B) Index map of Taconic and related klippen in northern and central Appalachians.

Continuous line: coast line

Dashed line with dots: overlap of Coastal Plain sediments

Line with three dots: river or lake-shore

Dashed line with ticks: western limit of Appalachian deformation

Black areas: larger ultramafic masses

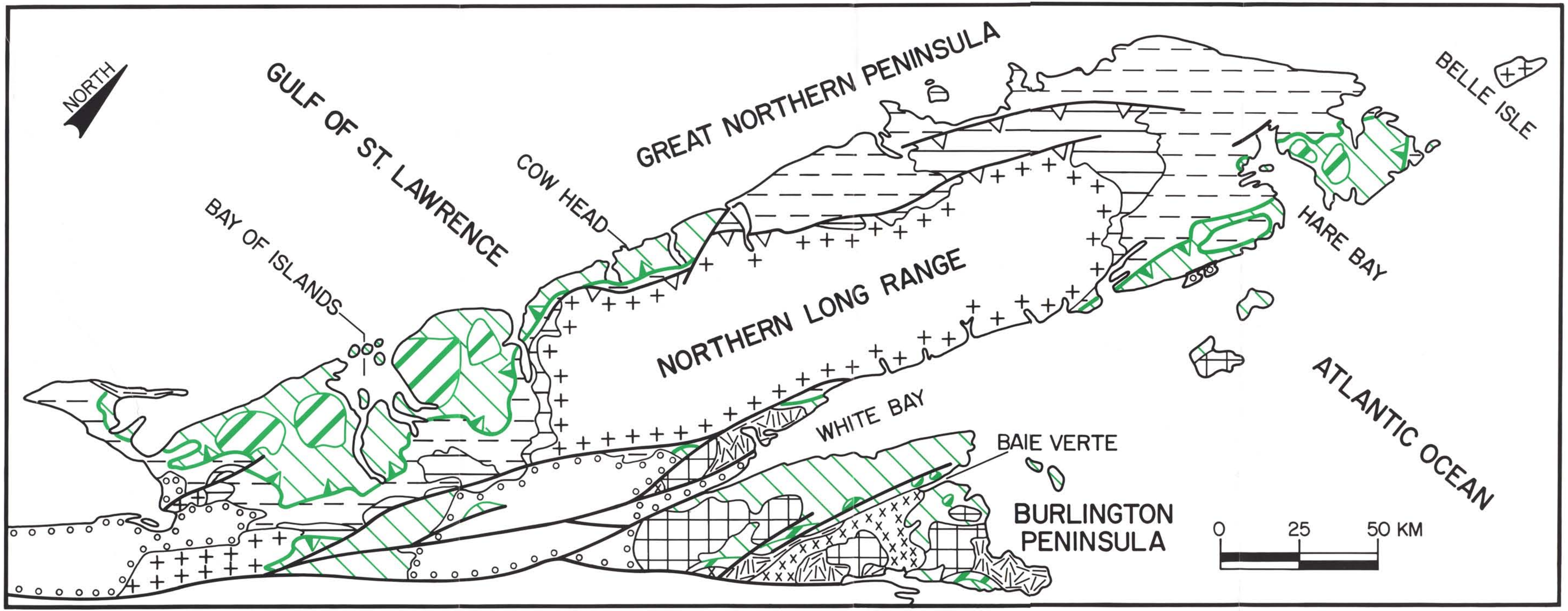
Green areas: outcrop areas of Taconic sequence

Black random dashes: Precambrian (Grenville) basement

Boxes—outlines of (A) and (C)

Letters, other than those indicating states and provinces:

Ad M—Adirondack Mountains
Hb—Hamburg, Pennsylvania
H R—Hudson River
J—Jutland, New Jersey
La M—Laurentide Mountains
L CH—Lake Champlain
M Ab—Mont Albert, Province de Québec
NYC—New York City
Qu—Québec (city)
SS—Shickshock Mountains
ST L—St. Lawrence River
SUS R—Susquehanna River
Th—Thetford, Province de Québec



C.

Fig. 6(C) Schematic tectonic map of western
relations of "Taconic" klippen.
Heavy black line without triangles: strike-slip
Areas bordered by small gray circles: Carbon
Black x's: Devonian granite
Medium black line with open triangles; thrus
Long Range massif (Devonian?)
Black cross-hatching: Ordovician granite
Black random dashes: Neoautochthonous st
dovician)
Heavy green bars tilted to right: Ultramafic r
pen
Green lines tilted to left: Rocks within klippe
brian) and possibly equivalent metamorphic rock
Heavy green line with half-filled triangles: T
pen and shale or slate at top of carbonate sequenc
Horizontal black dashes: Carbonate rock and
of carbonate sequence (Middle Ordovician to Low
Horizontal black lines: Quartzite and underly
quence (Lower Cambrian and late Precambrian)
Black crosses: Precambrian (Grenville) basem

question has been how large the olistoliths might be; blocks meters in size are unequivocal, but blocks hundreds of meters or kilometers long are contested (compare Rodgers, 1982; and Rowley and Kidd, 1982). For myself, I am willing to maintain that at least the western (and lower) slices or thrust sheets of which the Taconic klippe is made, tens to a hundred kilometers long, are such olistoliths within the autochthonous slate, though agreeing that during later deformation their borders have been utilized as or trimmed by thrust faults.

As the olistostromal deposits attest, the klippe arrived in the Middle Ordovician sea before deposition ceased there; the foundering of the carbonate bank (see above, p. 203) was probably caused by the klippe's forward progress, and the graywacke at the top of the carbonate sequence, which prograded far to the west of the Appalachian folded belt during the rest of the Ordovician, is material eroded from it. The rise of the "external massifs" of the Green sector was later, but whether Ordovician or Devonian, or both, is not certain (Rodgers, 1995, p. 471). Near Hudson, New York, two outliers of Lower Devonian strata (with possible uppermost Silurian at the base), Becraft Mountain and Mount Ida, overlie Taconic rocks unconformably but are themselves deformed.

Other Taconic klippen.—The Taconic slate mass of the type region is not unique in the northern Appalachians; similar masses of slate containing fossils too old for the slate to be in simple stratigraphic succession above dated carbonate sequences are now known from the northern tip of Newfoundland to the Susquehanna River in south-central Pennsylvania, a distance of over 2000 km, almost two-thirds of the length of the Appalachian chain (green areas on fig. 6B).

The mass in western Newfoundland (fig. 6C), which includes the well known Bay of Islands ophiolite complex, now seems particularly clear, but it took more than a decade of careful work and controversy to establish that it is a comparable klippe. When Schuchert and Dunbar (1934) described the stratigraphy of western Newfoundland, they found it hard to fit the various fossiliferous Ordovician units into a single, sensible stratigraphic sequence. Marshall Kay (see Kay, 1945, p. 442, but he was thinking along these lines 10 yrs earlier, Kay, 1935) was the first to suggest an allochthonous hypothesis, but his suggestion was published incidentally in an article with quite another purpose and was largely overlooked.[9] Rodgers and Neale (1963) revived Kay's hypothesis, asserting that the mass is a klippe comparable to that in the Taconics (which was then still in dispute) and including in it the Bay of Islands group of ultramafic bodies, later shown to display typical ophiolite stratigraphy; within about 10 yrs, this idea became generally accepted (Williams, 1969, 1971; Stevens, 1970). Furthermore, Rodgers and Neale (1963, p. 723-724) suggested that a similar mass of slate (also with ultramafics) on either side of Hare Bay at the north end of the Great Northern Peninsula of

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[9] Cooper (1936, p. 22-23; 1937, p. 11 ff.) had recognized the presence of large low-angle thrust faults beneath the ultramafic rocks in both west and north Newfoundland, but he did not see that much of the underlying sedimentary rock is also allochthonous.

Newfoundland, which they had never seen, is another klippe; Tuke (1968) confirmed their guess. To be sure, their conception of the klippen was far too simple; the work of Stevens (1970) and Williams (1969, 1971) showed that the Taconic-type sequence, recognized as such by Rodgers and Neale, forms only the lowest of several thrust sheets, the highest of which contains the ophiolite bodies (the same is true of the north Newfoundland klippe). Rodgers and Neale also pointed out (1963, p. 727-728) and Rodgers (1965) confirmed that the klippe rocks, already emplaced, were covered unconformably by "neoautochthonous" upper Middle Ordovician fossiliferous limestone; here the arrival of the allochthonous rocks is dated within two or three graptolite zones.

Figure 6C shows the relations around the Newfoundland klippen. The carbonate sequence ranges from Lower Cambrian to Middle Ordovician and has much in common with that in the Taconic region. The slaty sequence is astonishingly like the type Taconic sequence and was the clue that led Rodgers and Neale to the allochthonous hypothesis (thus Rodgers was able to predict the age of some of its units before fossils were discovered). The limestone-conglomerate bodies along the western margin of the type Taconic klippe are far outshone by those in western Newfoundland; in the section observable at Cow Head, numerous limestone-breccia layers and lenses, some with blocks the size of box cars, are intercalated through a shaly limestone succession about 1 km thick, dated by fossils to range from Middle Cambrian to Middle Ordovician (Kindle and Whittington, 1958). The higher thrust sheets on the other hand include bodies of basaltic volcanics (such volcanic rocks are quite rare in the Taconic area, but they do occur), and the highest thrust sheet, as already noted, is clearly made of great blocks, 10 to 20 km on a side, of oceanic crust and upper mantle, obduced along with the lower sheets over the carbonate sequence and its Precambrian basement, the latter exposed in the northern Long Range and a few smaller "external massifs" (Rodgers, 1995, p. 465).

The source of the Taconic sequence here and of the overlying thrust sheets must lie in west-central Newfoundland, well east of the northern Long Range; indeed a small klippe has been found on the eastern side of that range (Williams, 1977). In particular the ultramafic rocks may have their source in the Baie Verte line, a major tectonic line (suture?) on the Burlington Peninsula, but that part of Newfoundland has been much cut up by major, Carboniferous (and older?) strike-slip faults, and the source areas may have been displaced hundreds of kilometers laterally from their original position to the rear of the klippen.

In most of the Appalachian belt within the province of Québec, no lower Paleozoic carbonate sequence is visible; it appears only at the south border of Québec (at Philipsburg at the north end of Lake Champlain and in a couple of fault slices a little farther north), in a small window in eastern Gaspé at the other end of that belt, 700 km away, and also as the autochthonous cover of the Canadian shield northwest of and outside the Appalachian belt, where the basal quartzite is Lower Ordovician instead of Cambrian—indeed near Québec City the first deposits on the Precambrian basement are Middle Ordovician. The external zone of the Appalachians in Québec is structurally complex, consisting of several thrust sheets (St. Julien and Hubert, 1975), but the stratigraphy in those sheets has a great deal in common with the Taconic sequences in the Taconic region and in Newfoundland. (A higher volcanic sheet forms the Shickshock Mountains on the Gaspé Peninsula, and Mont Albert nearby may represent the ultramafic sheet; similar rocks reappear more internally in southern Québec, including the well known ultramafic bodies of the Thetford region, again of ophiolitic affinity.) All along the northwest margin of the external zone, however, there are limestone-conglomerates whose boulders were clearly derived from a Cambro-Ordovician carbonate sequence like those around the Taconics and in western Newfoundland (in places they even contain boulders of its Precambrian basement); clearly such a sequence was originally present as a continuous carbonate bank between the basin in which the Taconic strata were deposited and the Canadian shield. Perhaps the carbonate sequence was pushed up and out ahead of the Taconic thrust sheets and has since been eroded away, but more probably it is still buried beneath them, for seismic lines show that the autochthonous basement and its cover persist for tens of kilometers southeastward beneath the Appalachian thrust sheets (St.-Julian, Slivitsky, and Feininger, 1983, especially fig. 3). Finally, whereas in both the Taconic region and western Newfoundland the exotic rocks are in a klippe, separated from its roots by almost continuous belts of the carbonate sequence and by uplifts ("external massifs") of its basement, such belts are absent in Québec; the thrust sheets of Taconic rocks merge southeastward into the hinterland, whose structure is still more complex and includes the ultramafic bodies of the Thetford region, mentioned above.

South and southeast of the type Taconic klippe in New York State, similar rocks, but in deep amphibolite facies, overlie and are infolded with the Cambro-Ordovician carbonate belts and Precambrian massifs of western Connecticut and southeastern New York State all the way to New York City, where they were named the Manhattan schist. (No fossils are known in the schist in these areas, but a few have been found near the top of the carbonate sequence.) Farther west near Jutland, New Jersey, back where metamorphism is slight on the crest of the New York promontory of the North American craton, two or three small bodies of fossiliferous Taconic rock again overlie carbonate (Perissoratis and others, 1979).

In eastern Pennsylvania a much larger mass or group of masses of Taconic rocks, extending 100 km along strike and containing Lower and lower Middle Ordovician fossils, lies northwest of the principal band of Cambro-Ordovician carbonates in that region, surrounded by autochthonous slate and graywacke with upper Middle Ordovician fossils. Again Marshall Kay (1941) was the first to see that the relations are best explained by allochthony; the name Hamburg klippe, suggested by Stose (1946), is now generally applied to these masses. The north edge is unconformably overlain by Lower Silurian quartzite and locally by upper Upper Ordovician sandstone. Moreover, as both Kay (1941) and Stose (1946, p. 692-694) pointed out, the bulk of the metamorphic rocks formerly grouped as "Wissahickon schist" near Baltimore, Maryland, have a similar relation to the carbonate rocks and underlying basement there, though no fossils have been found that would confirm the allochthonous hypothesis.

Intermediate between the Hamburg klippe and the northern border of the "Wissahickon schist"—the Martic line or overthrust—another body of shale (the Cocalico shale) is preserved in synclinoria in northern Lancaster County, Pennsylvania. As Stose (1946, p. 690-691) mentioned, much of this shale has a "Taconic aspect," and a few graptolites seem to confirm an age older than that of the top of the underlying carbonate sequence.

OTHER EXAMPLES

Across much of the Great Basin in the state of **Nevada**—an area broken into large graben and horsts by Tertiary normal faulting that may have extended it by as much as 100 percent—is exposed a well characterized lower and middle Paleozoic stratigraphic sequence, beginning with Lower Cambrian (or even uppermost Precambrian) quartzite and reaching to uppermost Devonian to Lower Carboniferous shale but mostly made of carbonate rock. This miogeosynclinal or passive-margin carbonate sequence, clearly deposited on a gradually subsiding continental margin, thickens westward from 3 to 5 km. But in many of the ranges on the western side of the area there is another sequence, also kilometers thick but less well characterized because largely composed of badly deformed shale and argillite, with some sandstone, considerable chert, and local mafic volcanics (plus lenses of serpentinite). Though fossils (notably graptolites) are relatively few, it too ranges from Middle Cambrian to Upper Devonian. The sequences and their relations are well described by Roberts and others (1958).

It was fairly soon recognized that the shale sequence is thrust over the carbonate sequence on a major fault, the Roberts Mountains thrust (Merriam and Anderson, 1942). From the eastern outcrop of the shale sequence to the western outcrop of the carbonate sequence, visible in windows beneath the other, is now 90 km; though the large Tertiary extension may have roughly doubled the distance, the strong contrast between the two sequences and the local presence of transitional facies suggests an even larger displacement. In the shale at the top of the carbonate sequence are lenses and stratigraphic units of conglomerate made almost entirely of chert fragments from the shale sequence; their age (Early Carboniferous) thus dates the orogenic pulse, named the Antler orogeny by Roberts (1949, 1951), that emplaced the one sequence over the other, probably diachronously during the Early Carboniferous. The Antler orogeny was, however, only the first to affect this part of the Cordillera; orogenic pulses are also known in the Triassic and (probably almost continuously) from Middle or Late Jurassic to early Tertiary; this last orogenic period, called the Sevier orogeny, certainly redeformed both sequences (and the Roberts Mountains thrust) in Nevada and also the carbonate sequence and its later Paleozoic and Mesozoic cover to the east in the Western Rockies (Se, WR; Rodgers, 1990, p. 346-347).

The same two sequences can be followed northward from Nevada into Idaho, where however they become involved in metamorphism around the great Idaho bathylith. A very similar history is recorded in part of the Columbia Ranges of eastern British Columbia (behind the Canadian Rockies, CR), where the deformational pulse is called the Manitou orogeny.

In the southern **Ural,** as I have mentioned in an earlier article (Rodgers, 1995, p. 471-474, fig. 6, originally published as fig. 6, p. 348, Rodgers, 1990), a great thrust sheet brings ultramafic rock and associated sedimentary rocks (out of a starved basin east of the Ural Paleozoic carbonate bank) from east of the Ural-Tau anticlinorium (UT) out over the Devonian flysch that now fills the Zilaïr synclinorium next to the west (both anticlinorium and synclinorium are late Paleozoic, considerably later than the probably Devonian thrust fault, which they fold). West of the Ural-Tau, the thrust sheet is preserved in the Sakmara semi-klippe and the Kraka klippe; both were long interpreted as rooted uplifts or mushroom folds, but there was always a minority, allochthonous opinion, and drilling directed by M. A. Kamaletdinov (1974) showed that several kilometers of Devonian flysch underlie the Sakmara "uplift." In 1967 I visited a number of contacts around the Kraka ultramafic massif (localities spotted for me beforehand by N. P. Kropotkin, who held the minority opinion), and at each locality we saw cataclastic rocks dipping fairly gently under the ultramafic massif and away from the adjacent flysch.

Similar allochthonous masses are also known farther north, within the Northern and Polar Ural and in Pay-Khoy (PKh) and Novaya Zemlya (NZ; Zonenshain, Kuzmin, and Natapov, 1990, p. 33-35; they are not shown on fig. 6 of Rodgers, 1990 or 1995). Some seem to consist only of chert and argillite, like the Roberts Mountains allochthone in Nevada, others to include volcanic-arc deposits and mafic-ultramafic ophiolite complexes, as in western Newfoundland. It appears that the time of emplacement of these alloch-thones becomes younger northward.

The **Vourinos** ophiolite complex of northern Greece was one of the first such complexes whose petrology and internal structure were studied in detail (Moores, 1969), it is underlain by a couple of hundred meters of chlorite-sericite phyllite that rests on about 2 km of Triassic-Jurassic platform carbonate, moderately recrystallized but clearly of shallow-water facies (itself resting on a "Variscan" basement); all these rocks are overlapped by Upper Cretaceous (Cenomanian) limestone and Tertiary conglomerate. Those who had studied the complex before Moores considered it intrusive and rooted in place; indeed it was cited to me in the early '60s as an argument against the klippe hypothesis for western Newfoundland. To be sure, Moores (personal communication) suspected its allochthony, but his project was the internal, not the external structure of the complex, and he had no opportunity to follow up. When I visited it in 1966 with John Maxwell and Jay Zimmerman (after Moores' field work was completed), both were still convinced it was autochthonous, but the rather thin phyllite layer beneath proved to contain blocks (up to 100 m long) of several rock types not present in the underlying succession—a quite different limestone of deeper water facies (ammonitico rosso, Jurassic), radiolarian chert, mafic rocks, and even serpentine. The allochthonous hypothesis thus suggested was confirmed and documented by Zimmerman (1972), who showed that the emplacement of the complex is best explained by what is now called obduction (the word is Coleman's, 1971, p. 1216 ff.).

In the High **Himalaya** of the Zanskar region, resting above the well known Paleozoic, Mesozoic, and lower Tertiary stratigraphic sequence of the Tibetan zone, mainly sedimentary with much carbonate but itself strongly allochthonous, are a couple of large detached masses of ultramafic and mafic rocks, the Spongtang klippen (Frank and others, 1987, p. 269-270). Between them and the Lower Eocene strata at the top of the Tibetan sequence are—above—mafic to intermediate volcanic and volcanosedimentary strata (Dras unit, mid-Jurassic to mid-Cretaceous) and—below—silty slate and locally flysch, with limestone lenses, at least some of them interpreted as olistostromes (Lamayuru unit, Middle Triassic to Jurassic and probably Cretaceous); the upper unit is certainly in a separate nappe, and the lower unit probably is, for in places it is separated from the rocks above and below by serpentine mélange. Thus the situation is remarkably like that in western Newfoundland; indeed the different authors of the article cited (Frank and others, 1987, p. 268) espoused different hypotheses for the Lamayuru unit, the same ones in effect as those proposed for the various Taconic klippen (though everyone agreed that the Spongtang klippen are allochthonous). The source area for these rocks is certainly the Indus-Tsangpo suture zone some 40 km to the north; that zone now dips steeply south but, when the nappes now preserved in the klippen issued from it, it presumably dipped north, parallel to the great shear zone on which India was subduced under Asia. Other allochthonous masses of ultramafic rocks south of the Indus-Tsangpo line are present farther east in the High Himalaya, as in the Amlang La region.

In and behind the **Yangzi** fold belt (Yz) of south-central China (Rodgers, 1991, p. 843, fig. 9, and p. 845; see also Rodgers, 1995, fig. 9, p. 479) is a large sedimentary terrane called "Banxi," which in many areas contains mélange and pods of ultramafic rock and is mildly metamorphosed; fossils to date it are so far lacking. It was originally considered to underlie the carbonate-bearing sedimentary sequence (Sinian, that is, Upper Proterozoic, to Triassic) exposed in the main fold belt, but Hsü and others (1988) reinterpreted it as a great overthrust sheet of Taconic or Prealpine type, made of clastic sediments in large part coeval with the strata in the main belt. After some polemics, at least two of the disputants (Rodgers and Hsü, 1990) agreed that the original "Banxi" is a composite unit, including both a more or less autochthonous part, forming a clastic base for the carbonate-bearing sequence (but not in any sense its "basement"), and a strongly allochthonous part, containing the mélange and ultramafics.[10]

At the south foot of the **Dabieshan** part of the "Da–Qin–Long" fold-and-thrust belt (DQL; Rodgers, 1991, p. 843 ff., fig. 9; Rodgers, 1995, fig. 9, p. 479), in the Liuping area of southwestern Anhui, I was shown in 1986 a somewhat metamorphosed sequence, resting on Precambrian basement gneiss and consisting, from the bottom up, of quartzite, carbonate, phosphate rock, and schist with mafic lenses, all in greenschist facies. I wondered then and I wonder still if the sequence up to the lower part of the schist might be autochthonous Sinian to Lower Paleozoic, whereas the main body of the schist with the metavolcanics might be an allochthonous nappe, emplaced *before* the later folding and metamorphism (of Indosinian-Triassic-age), perhaps in a mid-Paleozoic orogenic pulse that is recorded by a clastic wedge in more external parts of that fold belt and into the Yangzi belt. We were told during our visit of Ordovician isotopic dates from the metamorphic rocks, but our guides held nevertheless that the metamorphic rocks and their metamorphism are Proterozoic, and they would probably reject my entirely speculative hypothesis.

CONCLUDING REMARKS

The "exotic" sequences or nappes I have described in this article are spread over all the northern-hemisphere continents (including North Africa), and the age of their emplacement ranges from Miocene (or more recent on the ocean floor west of Gibraltar and beneath the Po alluvium) back to Ordovician. They have however many common characters. They are exotic because in every region they rest on a standard continental-margin sequence having the same age span and almost invariably dominated by carbonates. (Why? Would they be harder to recognize if they rested on an entirely clastic sequence?) The exotic nappes arrived on top of that sequence before its deformation, or perhaps as that was beginning. The exotic sequences are dominated on the other hand by muddy rocks (shale, marl, mudstone, or argillite), though flysch is often present (as also generally at the top of the carbonate sequences), and there is very generally a strong contrast in sedimentary environment and fossils between coeval shallow-water carbonate below and deep-water shale, et cetera, above.

In many (but not all) the exotic sequences, ultramafic rocks—ophiolites—are present, generally in the highest nappe if there are several, suggesting that the exotic sequences were deposited, at least in part, on oceanic crust off the continental margins where the carbonate sequences formed. Moreover these exotic sequences appear to obey "Hess's Law," though that law was formulated for peridotites (Hess,

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[10] More recently, on the basis of new geochronometric data (Zhou and others, 1992), Hsü (1994) has reinterpreted the mélange- and ultramafic-bearing component of the "Banxi" as part of the older Precambrian basement for the carbonate-bearing sequence, which was nevertheless thrust over that sequence during the Mesozoic.

1937, p. 269 ff.); they were emplaced in the *first* major orogenic pulse in the orogenic belt of which they are a part.

The reason is not far to seek. As pointed out by Temple and Zimmerman already in 1969, a continental block forming part of a tectonic plate can approach a subduction zone only when the oceanic block beside it on the same plate is being subduced and eliminated; when the continent arrives it will attempt to go down the zone, and the oceanic crust *beyond* the zone, or a flake of that crust (along with any overlying volcanic island arc), will be pushed up—obduced—over the edge of the continent, bringing with it or under it sedimentary material from the oceanic block that has been subduced. The emplacement of oceanic over continental crust is of course inherently unstable; the subduction zone may flip to dip the other way, or it may be blocked and a new one formed somewhere else to accommodate the convergent component of the plate motions. Hence the restriction to the first orogenic pulse (or pulses) in each belt.

In many of the regions I have cited, a long controversy preceded the general acceptance of the allochthonous hypothesis for the exotic sequence (where it has been accepted); commonly it was the virtual contemporaneity of the two sequences that clinched the argument. Counterarguments (leaving aside simple fear of believing in such vast displacements) have been based partly on the absence of easily recognized thrust planes between the sequences and partly on the mechanical difficulty (often stated as impossibility) of moving the weak materials of which most of the exotic sequences are made for such great distances. It may be for these reasons that concepts of gravity sliding and flow have been invoked for many of these examples. For some authors gravity accounts for the whole of the horizontal displacement, powered by purely or mainly vertical movements in the source region, but for many of us who accept a major rôle for gravity it was nevertheless lateral compression—convergent tectonics—that produced the uplift permitting the sliding or flow. In many regions, after gravity had been proposed as the chief actor, a reaction set in, and compressive, subterranean thrusting is being stressed instead. Even for the Prérif "nappe," which for me is inexplicable except as gravity flow (and I fear I have so presented it), the rôle of gravity is being played down. It is a controversy much like that over the word "mélange," which could apply to rock bodies formed either by gravity at the surface (sedimentary mélanges or olistostromes) or by tectonics underground (tectonic mélanges), or more likely by some combination of the two (first sedimentary, then tectonic?), for both gravity and compression are operating constantly, if unevenly, in those peculiar settings where mélanges form. (Some authors indeed have simply decreed that the word "mélange" shall mean tectonic mélange, but the word is far too useful to be saddled with a strictly genetic meaning that might be proved wrong in many cases.) At any rate, I observe this conflict of interpretation—emphasis on gravity versus emphasis on compressive tectonics as the prime motor—in most of the regions I have described in this article. I hope that we can avoid approaching the facts from either extreme position—either/or—and can allow multiple working hypotheses to guide us as we struggle to understand each individual case.

ACKNOWLEDGEMENTS

I have already mentioned how Rudolf Ruedemann aroused my interest in the problems of the Taconic region in the early '30s; after that I visited him whenever I came back to Albany, and I was rewarded by the many, many entrancing stories he told me about geology and geologists (some of them not necessarily appropriate for a mere beginner). E-an Zen and I began working at the north end of the Taconic klippe at about the same time in the early '50s, and for his friendly openness in sharing discoveries as they were made I am forever grateful. Many other "Taconic" geologists have likewise shown me their field areas and freely discussed their findings.

Another geologist to whom I owe a very great debt is Professor Paul Fallot of le Collège de France, whom I first met as one of the guides for the 1952 excursion in the Rif and who accepted me in his laboratory and guided me to the best authorities during my "Alpine year," 1959–1960. For the Prérif I also wish to thank the other guides on that excursion, notably Doctors Marçais and Suter of la Service géologique du Maroc and the geologists of la Société chérifienne des Pétroles, who explained what their work—field mapping, dating by fossils, drilling—had found about the geology of the Prérif and presented us with their superb map based on that work (though it's tattered, I still have it). As I try to make clear above, their ideas were seminal for me in my thinking about the Taconics. I have visited Morocco several times since then; the last time, 1990, we returned to the Rif, and I was able to refresh my memory and to learn of the new ideas that have evolved there since 1952. For the Préalpes I wish especially to thank the group at Lausanne headed by Professor Badoux, that at Fribourg headed by Professor Tercier, and also Professor Trümpy of Zürich, who helped me to understand the klippen and the then-raging argument over the source of the Klippendecke. I have returned to the Alps many times since 1960; thanks to the kind offices of Professor Masson and the others at Lausanne, I was accepted there for two months in 1993, during which I brought my knowledge of the Préalpes up to date.

In 1960 also I was able to visit Italy, especially Tuscany, and to be shown its geology by the group at Firenze headed by Professor Merla and that at Pisa headed by Professor Trevisan. At that time I met Doctor Piero Elter, and I have profitted greatly by his recent syntheses of the Ligurian ensemble.

In 1987 I had the great privilege of a trip right across Turkey with Professor Ihsan Ketin, the "grand old man" of Turkish geology. We began in southeastern Turkey and visited the region of the Kevan gravity nappe, where Doctor Dogan Perincek's local knowledge was very helpful.

I have been able to visit many parts of Newfoundland with many different geologists, including Professor Marshall Kay, who first saw the necessity for an allochthonous hypothesis in western Newfoundland. Many of the other Newfoundland geologists helped Neale and myself by being very skeptical of our allochthonous ideas and forcing us to make them clear and consistent.

I have seen bits of the Roberts Mountain thrust fault and the two sequences it separates, notably with Thomas Nolan, Charles Merriam, and James Gilluly, and have argued about that region with them, Ralph Roberts, and many others.

In the Ural I was led to the Kraka massif by M. A. Kamaletdinov and B. M. Keller, and some of the localities we visited had been pinpointed for us by N. P. Kropotkin, though he was not with us there.

I went to the Vourinos with John Maxwell, who was visiting Jay Zimmerman in his field area there; again their initial skepticism about the allochthonous hypothesis helped me to clarify it and thus to bring them over to it.

I am particularly grateful to Professor K. J. Hsü for suggesting my participation in a trip in the lower Yangzi valley of China in 1986, at the time when he and his colleagues were working on their allochthonous hypothesis for the Banxi terrane; from what I saw on that trip I was able to suggest that the "Banxi" includes at least two very different sequences, whose map relations must still be thoroughly worked out.

Except for figure 2B, reproduced from figure 1 of Lévy and Tilloy, 1952, the figures were all drawn or redrawn by Carol Ann Phelps, and I wish to thank her once again for her careful drafting and her thoughtful proposals as we tried to work out expressive and consistent symbolism for the various figures. After the article was in draft, it benefitted greatly from the critical reviews of Mark Brandon and Darrel Cowan.

Why my geological paths have so often led me to regions where two different but coeval stratigraphic sequences are superposed is not very clear, but they have. And in my own field work and in trip after trip I have repeatedly stumbled onto "mélanges" or "block-rock" or similar rock types, and always they have led me to instructive and I think fruitful hypotheses, especially those concerned with the "gray area" where sedimentation and tectonics seem to merge into one complex process. Perhaps it is to the rocks themselves that I owe my greatest debt of gratitude.

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