

DRIVING FORCES OF MEDITERRANEAN OROGENY¹⁾

(Tyrrhenian Test-case)

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ABSTRACT

A critical review of newer data on the Tyrrhenian area (marine geology, land geology, paleomagnetism and seismicity) leads to a formulation of some general aspects of its evolution in Cenozoic time.

A solution is suggested for the geodynamic puzzle of Corsica and Sardinia, based on a relativistic structural analysis of the apparent rotations and translations of these islands with respect to a deforming continental frame.

During the Cenozoic the central Tyrrhenian area was subjected to pulses of doming and intervening periods of subsidence. The youngest uplift occurred in Mid-Pliocene time and thereafter it collapsed to bathyal depths at a rate of 1 mm/yr. This diastrophic evolution was accompanied by a geochemical transformation of the original continental type of crust (formed during the Hercynian orogeny) into an intermediary type of sialic crust (about 11 to 12 km thick). Meanwhile an orogenic crustal wave migrated radially outward from the Tyrrhenian centre of diastrophism, accompanied by radially outward directed overthrusts, imbrications, and other compressive tectonic features. The driving forces of this orogeny are evidently acting from the concave side of the orogenic arc.

The expectations of three geodynamic models of interpretation, advanced for the Tyrrhenian test-case, are compared with the observed aspects of its evolution. These models are (I) plate tectonics, (II) radiogenic heating by the continental crust, and (III) active mantle diapirism. It appears that only the third model provides an explanation which is consistent with the available geonomic evidence.

A. INTRODUCTION

Our geonomic knowledge of the Tyrrhenian domain has rapidly increased since the symposium on Mediterranean oceanization, organized by the Royal Geological and Mining Society of the Netherlands in 1968, the proceedings of which have been published in its Transactions nr. 26 (1969). Thereafter, the Tyrrhenian Basin has been investigated in detail by the oceanographical and geophysical researches of the Osservatorio Sperimentale at Trieste in collaboration with Woods Hole Oceanographic Institution in 1969 (Finetti et al., 1970; Morelli, 1971; Allan and Morelli, 1971; Zaruski et al., 1971), and by the laboratory of marine geology of Bologna in 1970 (Selli and Fabri, 1971). Cairo (1970) published an excellent review of our geological knowledge of the semi-circular orogenic arc around the Tyrrhenian Basin (Tell-Atlas, Sicily, Calabria, Southern Apennines). We now possess a great wealth of observational facts concerning the Tyrrhenian area. Consequently, this area of active volcanism, seismicity, and tectonic movements is excellently suited to be used as a test-case for the problem of the driving forces of orogeny: "What causes orogeny?". Are the expectations (prognoses) of the proposed geodynamic models of interpretation conform to the observational data (the diagnostic facts)? Or does the evidence provide indications that the concerning model is not a functionally correct representation of the observed geodynamic evolution? This is the prognoses-diagnoses method of verification of geonomic hypotheses (van Bemmelen, 1972b).

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For such a testing new relevant facts of observation concerning the Tyrrhenian domain will first be discussed; subsequently three geodynamic models will be tested, which have recently been advanced for the explanation of the orogeny in the Tyrrhenian area.

These three models are:

- I the geomechanical model of *plate tectonics*,
- II the geothermal model of *crustal radiogenic heating*,
- III the geochemical model of *mantle diapirism*.

It will appear that the testing of the first two models encounters serious discrepancies, whereas the third one is quite consistent with the available evidence.

B. SOME NEWER GEONOMIC DATA CONCERNING THE TYRRHENIAN AREA

a) Marine researches

The Tyrrhenian Basin is situated in the centre of

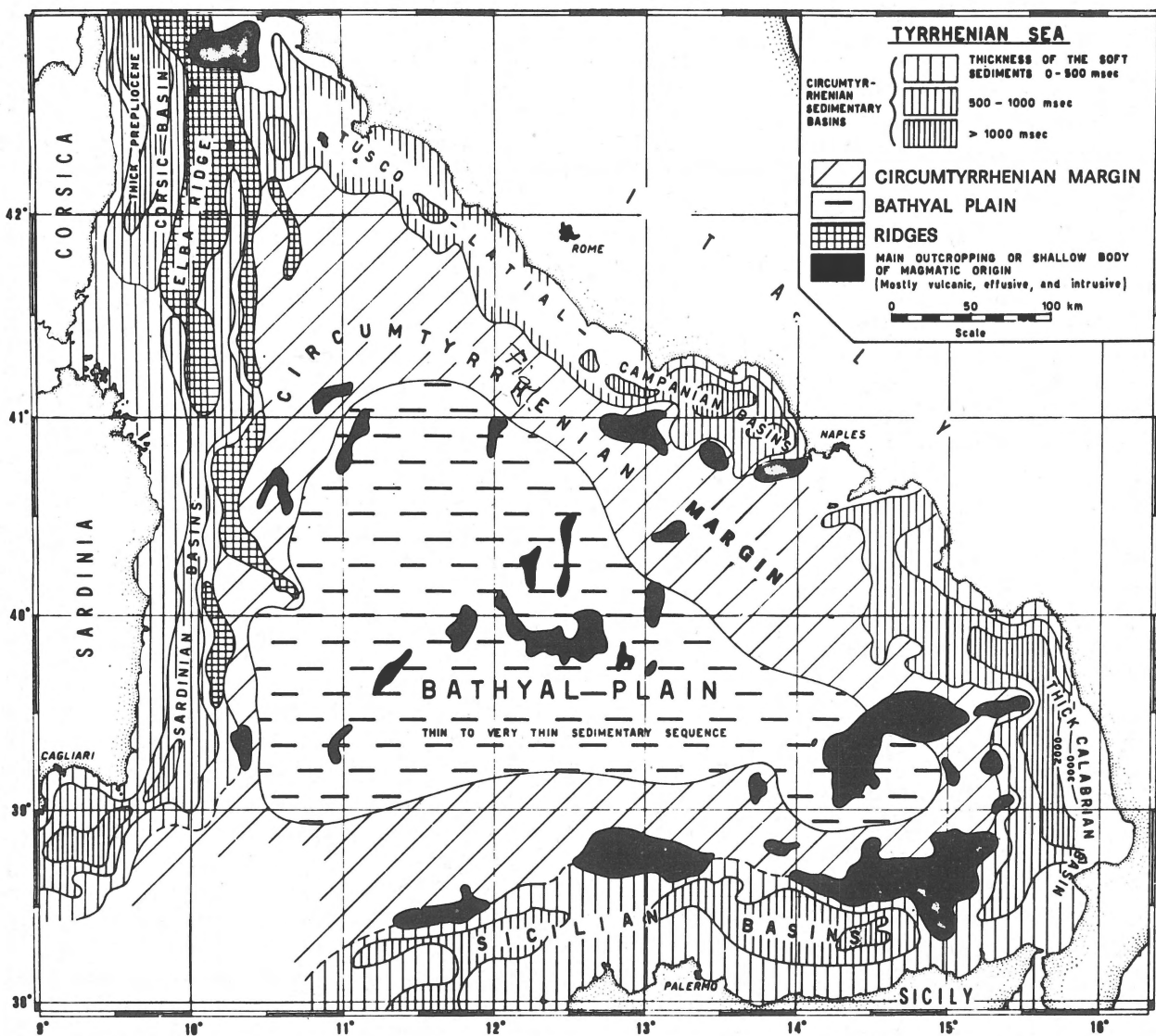


Fig. 1

Geo-morphological sketchmap of the Tyrrhenian Sea, according to Finetti, Morelli and Zarudzki (1970).

the Mediterranean Sea, being surrounded by a number of intercontinental small sea basins (the Balearic Basin to the west, the Adriatic Basin to the northeast, the Ionian Basin to the south east, and the Maltese Basin to the south). The basin is framed by the Corso-Sardinian block at its western side, and a semi-circular orogenic arc of the Alpine type along its northeastern, southeastern and southern sides (Southern Apennines, Calabrian Peninsula, and Sicily).

The Tyrrhenian Sea has a triangular outline with its base at the western side and its apex pointing ESE-ward.

The central part of the Tyrrhenian Sea is occupied by a bathyal plain (maximum depth 3600 m) with several extinct submarine volcanic cones rising to about 700 m below sealevel. This bathyal plain is covered by a thin veneer of Upper-Cenozoic sediments and it is surrounded by a circum-Tyrrhenian marginal rise, in which the thickness of the young, soft sediments increases to about 500 m.

Characteristic are the circum-Tyrrhenian sedimentary basins between the rise and the surrounding land. The separation between this sedimentary basin and the rise is formed partly by non-volcanic submarine ridges, partly by extinct or active volcanic ridges. The most prominent non-volcanic ridge extends from Elba southward at a distance of 50 to 100 km from the east coast of the Corso-Sardinian block. According to the interpretation of the seismic line MS-1 by Finetti et al. (1970, fig. 10A) this ridge is composed of westward dipping consolidated sediments, some hundreds of meters thick, resting on a crystalline basement complex. The ridge is pushed eastward along upthrusts, which apparently also affect the soft Late-Cenozoic sediments of the central basin.

The most pronounced marginal basin is the Calabrian one, called Paola Basin by Sellì and Fabri (1971), which is situated at the eastern apex of the triangular Tyrrhenian basin, where the soft sediments reach a thickness of over 3000 m (see fig. 1).

Sellì and Fabri (1971) distinguish seven morphological units (see fig. 2). The generalized W-E profile across the Tyrrhenian Sea, south of the 41°N parallel (inset of fig. 2), shows the average widths and depths of these units: a) continental shelf, b) upper continental slope, c) peri-Tyrrhenian basins, d) peri-Tyrrhenian seamounts, e) lower continental slope, f)

bathyal plain, g) central-Tyrrhenian seamounts.

The peri- or circum-Tyrrhenian sedimentary basins are bordered by seamounts and ridges or insular volcanoes, i.e. Pontine Islands, Stromboli and Aeolian Islands, which act as dams that retain the terrigenous sediments, carried through canyons cutting the upper slope.

The laboratory of marine geology of the university of Bologna made during its first Tyrrhenian cruise (July 1970) a detailed survey by continuous seismic reflection of the Gioia Basin (north of the Straits of Messina), the Sardinia Basin (east of Sardinia), and two areas of the bathyal plain. Three main seismic units could be distinguished, designated A, B, C, which are usually separated by nonconformities. The basal nonconformity of unit A normally overlies the unit B and, in places, the unit C. This widespread nonconformity corresponds in age to the extensive regional transgression, well known in Italy and Sicily along the Tyrrhenian coasts (Tuscany, Latium, at scattered places in Southern Italy and Sicily), but chiefly in the foredeep of the Apennines (extending uninterruptedly from the Po Basin to central Sicily). The age of this nonconformity is generally the early Pliocene or the Middle Pliocene; it is succeeded by a post-tectonic Plio-Pleistocene continuous sedimentary sequence; apparently the Apennine orogeny ended before this nonconformity was produced.

These new data reported by Sellì and Fabri (l.c.) indicate that during the Middle Pliocene the Tyrrhenian area was emerged to a large extent, resembling an archipelago of numerous islands, like the present Cyclads in the Aegean Sea, separated by sea-channels and sounds.

Starting at the Middle Pliocene a tremendous foundering of the Tyrrhenian area took place. The surface, corresponding to the Mid-Pliocene sealevel, was lowered to about 740 m depth at Baronie Seamount (central part of the submarine ridge east of the Corso-Sardinian ridge), to 1,800 m in the Stromboli Canyon, and finally to 4,500 m in the deepest part of the bathyal plain. Assuming the more recent absolute ages (Sellì, 1970), the Middle-Pliocene began 4.7 or 3.9 million years ago; therefore the average rate of foundering was about 1 to 1.1 mm/year. Thus Sellì and Fabri conclude that the formation of the present deep Tyrrhenian Sea began in the Middle Pliocene and may well be the youngest deep sea basin of

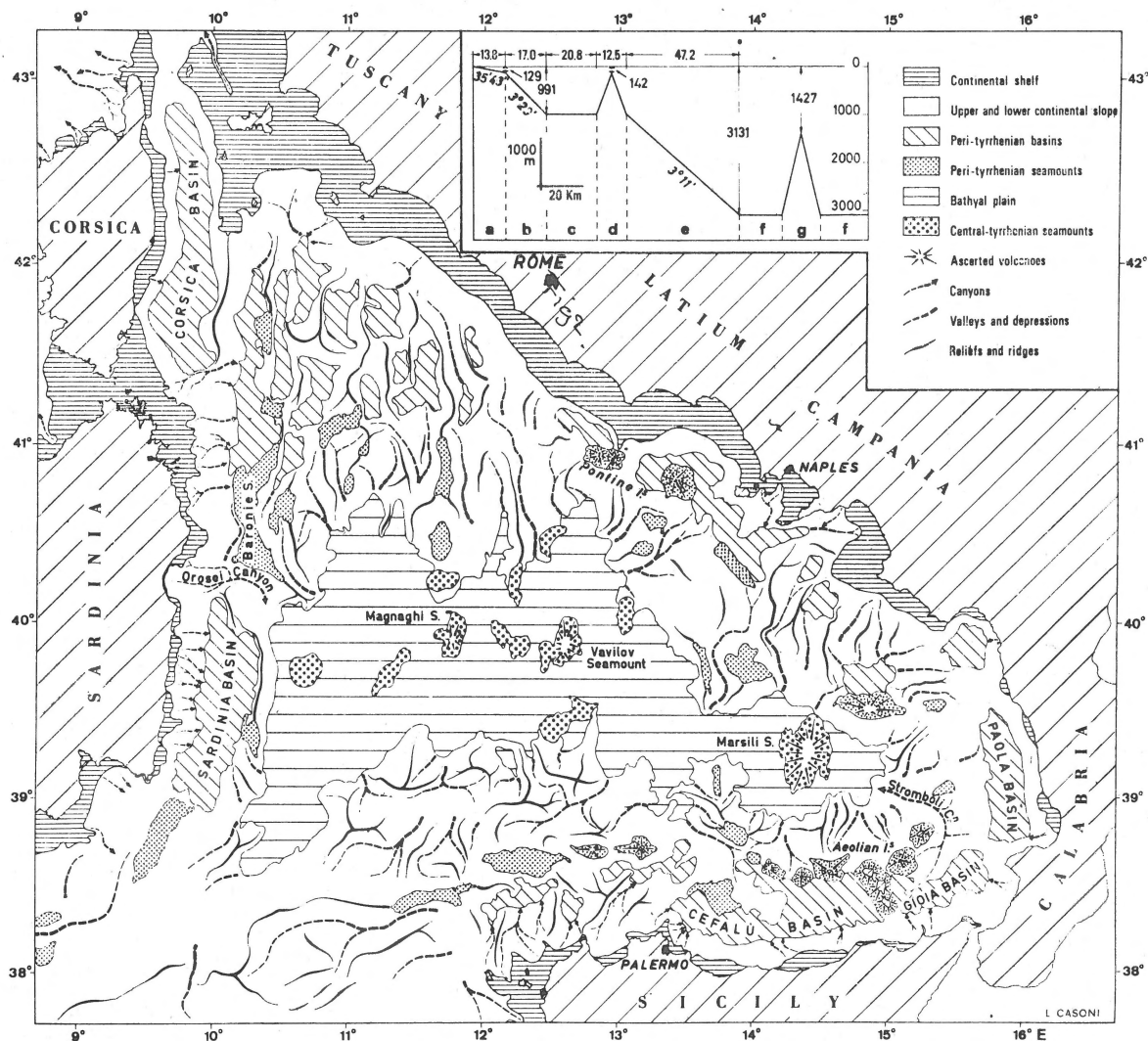


Fig. 2
Geo-morphological sketchmap of the Tyrrhenian Sea, according to Selli and Fabri (1971).

the world. The Mid-Pliocene nonconformity lies today at depth of 4,500 m and the thickness of the post-tectonic sediments deposited on the bathyal plain amounts to maximum 900 m.

During this Pliocene to Quaternary collapse the Tyrrhenian crust underwent a general extension in W-E direction, accompanied by normal concentric faulting on the continental slope and by N-S faults in the bathyal plain. Along the concentric faults anatectic or hybrid, rarely basaltic, magma caused the circum-Tyrrhenian volcanism, which is partly still active.

It represents the volcanic inner zone of this part of the Alpine Mountain System of the Mediterranean area (Tuscany, Latium, Pontine Islands, Campania, Stromboli and Aeolian Islands). Along the second (N-S) set of faults in the bathyal central part basaltic magmas ascended from the asthenosphere (Geomountains of Marsili, Vavilov, Magnaghi, etc.). According to the recent radiometric dating almost all of these volcanoes are younger than 4.5 to 5 million years, mostly only 1 million years.

Selli and Fabri state that the upper half of

the seismic unit B is of early Pliocene to early Middle Pliocene age, as proven by dredging in the Stromboli Canyon; the lower part of the B sequence may well be correlated with Sicily and Calabria sequences. Therefore its base should correspond to the transgression of the Lower Miocene, well known in Southern Italy, Sicily and Sardinia. Before this time a very extensive part of the Tyrrhenian area was emerged, being surrounded by a semi-circular ring-depression where now the orogenic arc of the Southern Apennines, Calabria and Sicily is situated. Enormous gravity nappes of the sedimentary cover of this central Tyrrhenian tumescence were emplaced by radial slides into the marginal depression. This tectonic denudation by décollements removed a great part of the sedimentary epiderm from the central Tyrrhenian dome.

The available data on the pre-Miocene basement, viz. seismic unit C distinguished by Sellì and Fabri, are scarce. Metamorphic rocks and Paleozoic rocks (Baronie Seamount) have been dredged, but probably younger sedimentary rocks are present as well.

These modern marine researches have established three geological events in the Tyrrhenian area, a Lower Miocene transgression, an Apennine-Calabrian-Sicilian orogeny, and a Middle Pliocene transgression. During the foundering another environmental event took place in the Tyrrhenian area, the so-called "crisis of salinity" of late Miocene age (Messinian), which gave rise to extensive evaporitic sediments in the Mediterranean area.

The Upper-Cenozoic volcanic activity in the Tyrrhenian area testifies to the important role that geochemical processes in the underlying mantle played during its geodynamic evolution.

b) Geophysics

The Tyrrhenian basin is an area in which geodynamic processes are very active. It is characterized by high magnetic and gravity anomalies and high heat-flow, combined with Plio-Pleistocene volcanic activity. Sub-Moho velocities of seismic waves are relatively low, of the order of 7.7 km/sec for the Pn wave. This subcrustal velocity is already reached at a depth of about 11 to 12 km. The low-velocity-channel or asthenosphere reaches upward to a depth of about 50 to 60 km, forming an ultra-low-velocity-channel with

transverse wave velocities of only 4.1 km/sec. Ritsema (1972) concludes from these extreme geophysical conditions that exceptional processes are active in the upper mantle underneath the Tyrrhenian basin.

The occurrence of an Ultra-Low-Velocity-Channel in the base of the lithosphere means that not only a density inversion is present, but also a "viscosity inversion" (Patalakha, 1971). The latter circumstance greatly invigorates the buoyancy of the U.L.-V.C. in the presence of deforming stresses in the surrounding medium. This leads to an accelerated diapirism of asthenolithic bodies, the rise of magmatic pockets, and their eventual squeezing out toward the surface.

The seismicity is of special interest for the interpretation of the geodynamic processes which are in progress in the Tyrrhenian region. In this field the researches of Ritsema deserve special attention (1969, 1970, 1972). Three groups of shocks can be distinguished: (a) crustal seismicity, (b) foci at an intermediary depth, and (c) deep foci.

(a) The crustal seismicity is rather high in the orogenic arc which surrounds the Tyrrhenian basin at its NE, E, SE, and S sides. The focal depth rarely exceeds 60 km. The Corso-Sardinian block at its western side is notably free from crustal earthquakes.

(b) A cluster of foci at depths ranging from 200 to 350 km occurs underneath the ESE corner of the basin, opposite to Calabria. A computer program for the re-location of these intermediary earthquake foci, using available P wave data, resulted into a rather compact cluster (Ritsema, 1972, fig. 2). The ESE-WNW cross-section of this cluster is pearshaped with a curved axis, concave to the west, pointed at its top and about 70 km wide at its base. The projection of the foci on a SSW-NNE trending vertical plane has a height of 130 km and a width of about 210 km. Ritsema (1.c) remarks that this deforming mass is rather a narrow tongue than a downplunging lithospheric slab.

The fault-mechanisms in the foci of seven stronger Tyrrhenian earthquakes have an identical orientation, as is indicated by our figure 7. There are four possible solutions: the motion is either of the block-faulting type with a strike in NNE direction and the western block rising with respect to the eastern one, or the eastern block subsiding with respect to the western

one; or of the thrust type in which the upper block overthrusts the lower block in WNW direction, or the lower block underthrusts the upper block in ESE direction. Maximum pressures (P-axes) plunge about 60° WNW, minimum pressures (tension axes) rise about 30° WNW.

No foci of earthquakes have been observed at the depths of the low velocity layer between 100 and 200 km. This indicates that the asthenosphere is not traversed by a rigid lithospheric slab. It looks as if a tongue of new material is introduced from the asthenosphere into the underlying sclerosphere (or mesosphere), with internal pressures directed in the dip direction at the top of the tongue-shaped body. At the base of the tongue, at 300-350 km depth, tensional movements may prevail, producing its westward concave outline (see figure 7).

It should be pointed out, however, that — as far as Ritsema's technique of the seismic interpretation of the fault-mechanism in the Tyrrhenian earthquake foci is concerned — each of the above-mentioned four solutions is possible. The arrows in figure 7 are merely suggestions by the present author, indicating for individual shocks which block might have been actively displaced in relation to its surroundings. These suggestions are not diagnostic facts, but a hypothetical amplification of the mechanical picture, based on the concept of two independent though interacting circuits of matter occurring in these parts of upper mantle (see discussion of model III in chapter C).

(c) Two deep foci between 450 and 500 km depth have been observed under the centre of the Tyrrhenian basin. A vertical gap of 120 km separates these deep shocks from the cluster of intermediary shocks. Therefore, the deep shocks might not be directly related to the stress pattern of the latter. One might rather think of sudden volume-changes of mineral phases at these depths, as is also accepted for the seismic maxima at these depths under the Japan Sea.

c) Geology

The Tyrrhenian basin is surrounded by a frame of structural units which rise above sealevel, and about which we possess a fairly detailed geological knowledge.

Distinction has to be made between (c' the Corso-Sardinian block at its western side and (c'') the semi-

circular orogenic arc along the remaining part of its contour.

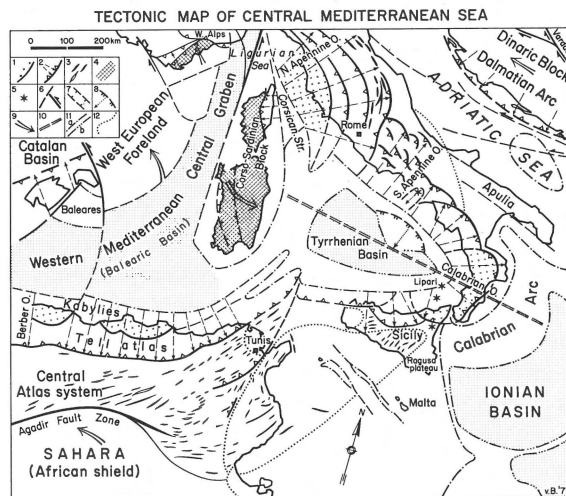


Fig. 3

Schematic tectonic map of the central part of the Mediterranean, according to van Bemmelen, 1972b, and adapted from Caire (1970).

Legend: 1 = Inner zones of orogenic arcs, with outcrops of the pre-Alpine basement complex and Cenozoic intrusive and/or extrusive igneous rocks; 2 = Outer zones of orogenic arcs with nappes of non-metamorphic sediments. Arrows indicate the areas of provenance and the direction of the overthrusting movements; 3 = Fold trends of non-metamorphic sediments in adjacent strips of foreland (Africa, Sicily, Italy); 4 = Sialic crustal blocks of Corsica-Sardinia and Maures-Esterel, which are remnants of the sialic continental crust that originally formed the floor of the western Mediterranean; 5 = active volcanoes in and around the Tyrrhenian centre of diastrophism; 6 = shear faults with indication of the sense of displacement of the side that actually was displaced according to a relativistic structural analysis; 7 = Sardinian graben; 8 = suggested reversed slides towards the central bathyal part of the Tyrrhenian collapse basin (one between the 3000 and 1000 m isobaths, and one cutting across the Somma, presumably being the cause of its eruption in 69 A.D.); 9 = rotative translations of crustal units in the western Mediterranean area; 10 = axis of symmetry of the Tyrrhenian orogenic system and location of the section of fig. 7; 11 = isobaths of the Mediterranean basins: a is the 1000 m and b the 3000 m isobath; 12 = limits of Plio-Pleistocene areas of subsidence and the outside of the circum-Tyrrhenian orogenic arc, the foredeep between Tunisia and Sicily and the foredeep of the southern Apennines.

c') The geodynamic puzzle of Corsica and Sardinia. — The Corso-Sardinian block is a microcontinental

structural unit, about 500 km long in N-S direction and about 150 km wide, with a Moho-discontinuity at about 30 km depth. The crustal thickness of the adjacent Balearic Ligurian and Tyrrhenian basins is only about 11 to 12 km.

It has been suggested on geological grounds that this crustal slice was once situated much closer to the southeast coast of France, and that it attained its present position by a counterclockwise rotation. De Jong et al. (1969) and Zijdeveld et al. (1970) published paleomagnetic data in support of this hypothesis; Alvarez (1971, 1972) adduces newer geological and paleomagnetic data that the rotation occurred in Late Cenozoic time, and suggests a pole of rotation situated north of the northern tip of Corsica, at $43^{\circ}22'N$ and $9^{\circ}38'E$. The thesis that the Ligurian sea between the SE coast of France and the Corso-Sardinian block is a young sphenochasm seems to be well founded. The rotation of Sardinia amounts to some 50° . Its lateral movements apparently terminated in the Quaternary, because the younger sediments in the central, NW-SE trending graben of the island are no more deformed, the volcanic activity is extinct, and it is no more seismically active.

Alvarez (1972) discusses the rotation of this micro-continental block in terms of plate tectonics. The island block was probably close to or touching France during at least part of the Tortonian (12.5 to 7.0 m.y.). If this is so, the rotation can have begun no earlier than 11 to 12 m.y. ago. On the other hand, the rotation should have terminated already in the Upper Miocene (Messinian), because of the presence of salt domes beneath the floor of the Ligurian Sea (7.0 to 5.0 m.y.). So the maximum time range during which the rotation can have occurred is 11.5 to 6.0 m.y., allowing 1.0 m.y. of Tortonian before and 1.0 m.y. of Messinian after the rotation (Alvarez, 1972, p. 103).

This picture is obtained by considering the Corso-Sardinian block as a structural unit so that the islands cannot have rotated separately, and by surmising that the structural frame of France and Italy was stable during that time. Both premises are questionable. A relativistic structural analysis of the tectonic evolution of this part of the Mediterranean in Cenozoic time leads to a different, much more complicated combination of tectonic processes.

Three points have to be borne in mind: *First*, the

Corso-Sardinian block not only rotated, as is indicated by paleomagnetic researches, but it can also have been translated eastward and northward, which is not detectable by studies of the vector of remanent paleomagnetism. *Second*, the structural frame of the western Mediterranean basin was deformed during the Cenozoic by mega-tectonic processes acting from the outside of this region and by meso-tectonic processes acting from the inside. *Third*, the Corso-Sardinian block probably never traversed the central graben system of the western Mediterranean, which developed in the Ligurian area probably already since the end of the Mesozoic.

These three points will be shortly elucidated hereafter.

1) The Cenozoic rotation of Sardinia can be accepted as a diagnostic fact (de Jong et al., 1969; Zijdeveld et al. 1970; Alvarez, 1972), though the location of the axis of this rotation is not directly measured and questionable. An eastward translation of the Corso-Sardinian block is not measurable paleomagnetically, because such a drift movement does not influence the direction of the vector of RPM. The observation that the submarine N-S trending ridge, east of this block, is thrust eastwards against the youngest sediments of the Tyrrhenian Basin (Finetti et al. 1970) indicates that such an eastward translation may have proceeded up to the Quaternary.

A northward translation of one or two hundreds of kilometers is neither indicated paleomagnetically, because this would hardly change the inclination of the RPM-vector. However, there are geological observations which do indicate such a northward translation. East of Genua the N-S trending Sestri-Voltaggio fault is an important left strike slip fault of Cenozoic age. At its northern end, near to the southern border of the Po Basin, an east-west trending, asymmetric syncline of Tongriano flysch is found. This sandstone-marls sequence of about 1000 m thickness covers unconformably strata of the north-western tip of the Apennines, which had been deformed by the Ligurian phase of tectogenesis (Lower and Middle-Eocene). A revival of the tectogenesis in Oligo-Miocene time produced the submarine E-W trending syncline of Villanervia-Bobbio, whilst its filling by turbidity currents continued (Ibeken, 1972). These observations indicate that the north-

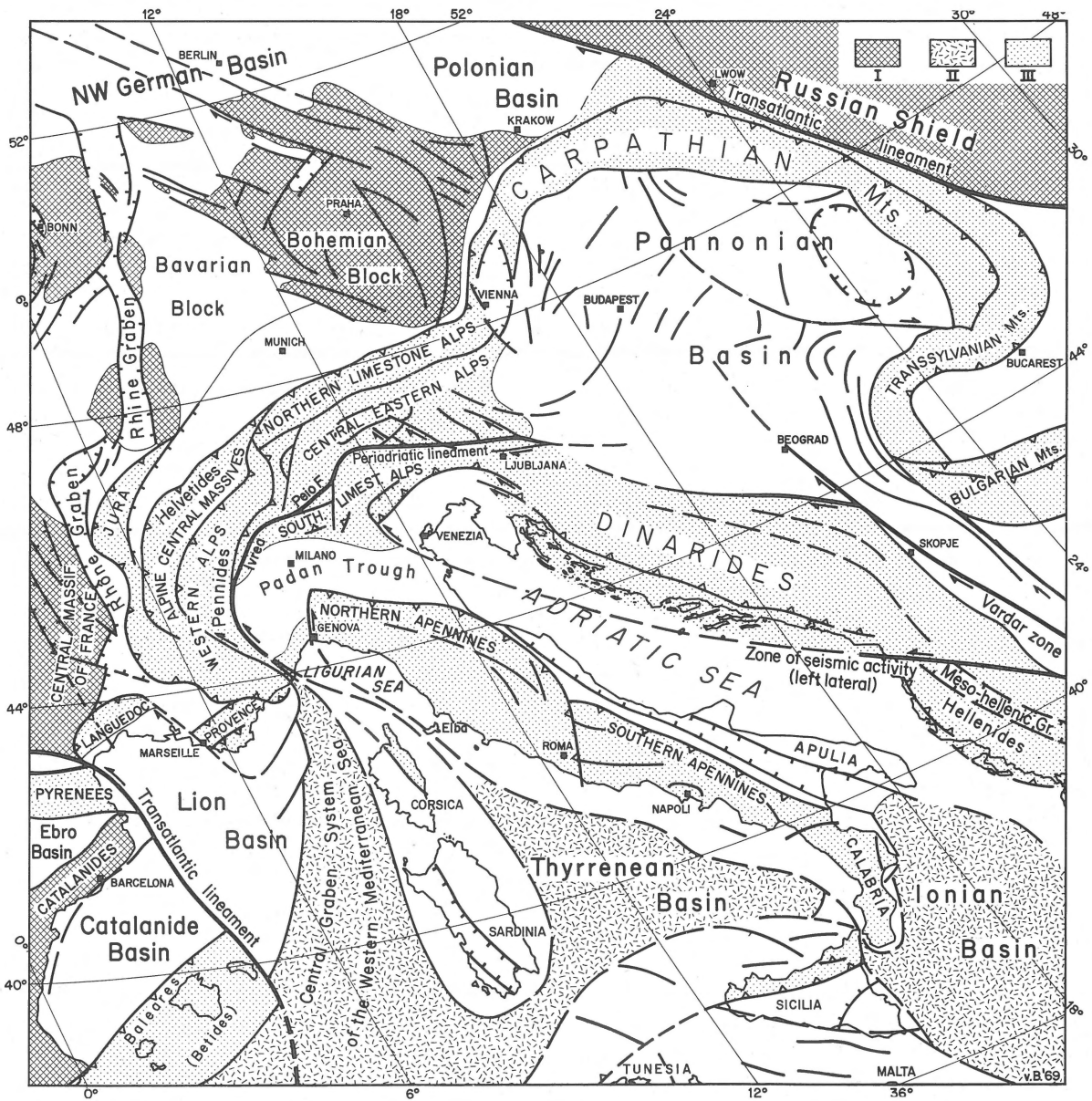


Fig. 4
Schematic tectonic map of central Europe, according to van Bemmelen (1969b).

Legend: I = exposures of sialic continental crust in the European foreland of the Alpine mountain system; II = bathyal parts of the Mediterranean Sea underlain by an intermediary type of crust; III = fold- and overthrust-belts of the Alpine mountain system.

ward translation of the Corso-Sardinian block along the eastern side of the left-shear zone of Sestri-Voltaggio may have continued to as late as Oligo-Miocene; though de B o o y (1969, p. 88) advances convincing arguments, based on his researches of sedimentary detritus, that the Sestri-Voltaggio lineament had become already a tectonical divide during the Lower Tertiary (pre-Middle Eocene). This brings us to the next point, which says that the present outline of the Ligurian deep-sea basin is a younger feature and that it can not be considered as a fixed structural frame for a swinging micro-continental plate, as suggested by A l v a r e z (1972).

2) A l v a r e z (l.c., fig. 2) considers the NW-SE trending boundary between the Balearic-Ligurian deep-sea basin and the Balearic Islands as a transform plate-margin with a right offset, which "must lie there" (quotation), because of the supposed mid-Cenozoic rotation of the Corso-Sardinian block. However, such a palinspastic reconstruction has the consequence, that the Betic chain is abruptly cut off, and that nowhere its eastward extension is found. The present author pointed out (1969), that this NW-SE end of the Balearic chain of islands is the beginning of a transatlantic lineament, a left shear zone, which extends northwest- and westward, by way of the Gulf of Biscay, along the southern margin of the British Islands and Ireland, to the Reykjanes ridge which is offset by it at its southern end in a left direction over hundreds of kilometers. This left mega-shear zone at the southwestern side of Central Europe forms the counterpart of a right mega strike slip zone at its northeastern side, which forms the boundary with the Russian shield (fig. 4; and v a n B e m m e l e n, 1969, fig. 3). Between both trans-Atlantic lineaments Central Europe has been extended in northwest- respectively westward direction, in the wake of the westward spreading Thulean Basin, (phase III of the Atlantic mega-undation; v a n B e m m e l e n, l.c., table III). A result of this mega-tectonic process is that the southeast coast of France is pulled away from the Mediterranean; this is yet another cause of deformation of the continental frame of the Ligurian Sea in Cenozoic time.

A consequence of this palinspastic reconstruction is that the eastward extension of the Balearic chain of islands with their NW-ward overthrust structures appears to be represented by the Languedoc arc

around the Gulf of Lion, which also shows Upper-Eocene NW-ward overthrusts (E l l e n b e r g e r, 1967). The left offset between the front of the epidermal overthrusts amounts to some 300 km. But these overthrusts of the sedimentary coat (epiderm) have only a shallow draught, so that the offset of the underlying metamorphic basement complex may have been much smaller. The strait SE-NW trending part of the 2500 m isobath, which borders Menorca at its northeastern side, shows a left offset of almost 150 km (P a n n e k o e k, 1969, plate I opposite to p. 64). This amount might represent the real offset of the underlying sialic crust between the Balearic islands and Central Europe along the left-lateral, trans-Atlantic mega-shear zone.

The eastward extension of the Languedoc arc is represented by the W-E trending Provence arc. Both sections are separated by a right shear zone, which extends from Marseille northwestward. The basement complex of the Provence arc appears in the massifs of Maures and Estérel, and its W-E trending epidermal overthrusts and folds are directed northward. The compressive structures of the Provence arc came into being during the orogenic phase which lasted from Upper Cretaceous to Mid-Eocene. At their eastern side they are re-deformed by the cross-folding, N-S trending compressive structures, which belong to younger orogenic phases of the Western Alps (L e m o i n e, 1972).

This palinspastic reconstruction of the north-western continental boundary of the Mediterranean shows that the Betic Cordilleras, the Balearic chain of islands, the Languedoc arc, and the Provence arc form a structurally consistent series of compressive structures which are radiating outward from the complex system of diastrophic centres (Alboran, Balearic, Ligurian) in the western Mediterranean Sea. They all are situated at the concave side of the arcuate central graben system which traverses the West Mediterranean Sea from Gibraltar to Genua. This graben system can be compared in size and structural character with the Gayman Trench in the Caribbean area. It is a coherent structural element and it is highly improbable that the orogenic arcs at its concave (north-western) side once occupied positions at its convex (southeastern) side.

The same can be said of the structural units at the convex (southeastern) side of the central graben

system. These are the orogenic arc of the Northern and Southern Apennines, Calabria, Sicily, the Tell-Atlas chains, and the Rif-Gibraltar arc, whilst the microcontinental unit of Corsica and Sardinia occupies a more inward position, adjacent to the eastside of the central graben. This brings our relativistic structural analysis to the third point, the original position of the Corso-Sardinian block with respect to the central graben system of the Western Mediterranean Sea.

3) It is our thesis that the Corso-Sardinian continental block did not traverse the central graben. The islands of Corsica and Sardinia may have rotated counterclockwise and translated somewhat eastward and northward in Cenozoic time, as is indicated by paleomagnetic and tectonic observations. From the viewpoint of plate tectonics the objection against this thesis might be raised, that the amount of rotation of Sardinia amounts to about 50° and this rotation would bring the Corso-Sardinian block in a position close to the present SE-coast of France, that is at the concave inner side of the central graben system. However, it is by no means certain that Corsica and Sardinia rotated as a structural unit around a pole near to the northern tip of Corsica. It is quite possible, if not probable, that both islands rotated independently, Corsica about 21° (Westphal, 1967) and Sardinia about 50° , around axes situated somewhere in their geometrical centres. Arguments for this interpretation are firstly the different amounts of their counterclockwise rotations; secondly the morphology of the Strait of Bonifacio between them, which indicates a right E-W trending strike-slip movement between both islands, as should be expected in case of independent counterclockwise rotations of both islands. Thirdly, the strongest argument for this view is the fact, that the Campidano trough on Sardinia, which trends from Gagliari northwestward, makes an angle of 50° with the eastern margin of the adjacent central graben of the western Mediterranean. These graben-structures probably originated in Mid-Cenozoic time by extension of the crest of the Balearic dome. Therefore, the west Mediterranean graben and the Campidano graben were originally subparallel, and the angle of 50° originated by later rotation. This extension of the crest of the dome is a geodynamic process of meso-tectonic dimensions, which occurred

probably in combination with the extension of Central Europe in northwestern direction. The latter is a geodynamic process of mega-dimensions. The central graben of the western Mediterranean and the adjacent central graben of Sardinia were originally sub-parallel features of crustal extension. Thereafter, the south-east- and eastward spreading of crustal waves (during the collapse of the West Mediterranean centres of diastrophism), caused some surf-riding movements of the Corsican and Sardinian blocks, with individual rotations, and combined eastward as well as northward translations. For Sardinia this rotation resulted in the present angle of 50° between the central graben of the island and the adjacent central graben of the western Mediterranean.

A characteristic difference between the northwestern and the southeastern parts of the circum-West-Mediterranean orogenic belts is that the outward spreading crustal waves are less developed in the former than in the latter group. The eastward spreading of the northern Apennines has been analysed by Wunderlich (1967). The orogenic development began already at the end of the Mesozoic with the subsidence of a marginal depression around the eastern side of the central Ligurian dome. The Upper Cretaceous to Lower- and Mid-Eocene sediments in this depression were folded and subsequently elevated at the beginning of the Cenozoic, and then the marginal depression migrated gradually eastward as the foredeep of the crustal wave which brought the northern Apennines into existence. In the course of its Cenozoic evolution this orogenic wave differentiated into a volcanic inner zone and a non-volcanic outer zone characterized by overthrust structures which are directed radially outward, toward the present foredeep.

The volcanic inner zone extends from the east coast of Corsica towards the Toscanide belt of the northern Apennines. It is characterized by subparallel isochrones of its igneous activity, beginning with maximum radiometric ages of 9.5 m.y. in Capraia, about 25 km off the northernmost tip of Corsica, then smoothly decreasing eastward, via the granites of Elba (7 – 6.4 m.y.), to the westcoast of Italy (about 5 m.y.) and ending in the extinct volcanic province of Latium around Roma (about half a million years old).

Alvarez (1972) gives a mechanically rather incomprehensible interpretation of this Cenozoic geo-

dynamic evolution in terms of plate tectonics. The fossil trench of the rotating Corso-Sardinian block is supposed to be located between these islands and the system of submarine ridges, which extend from Elba southwards (1.c. fig. 2a). "... rotation ceased when Corsica and Sardinia jammed in the trench." ... "the leading edge of the plate, presumably derived from thinner crust, broke loose and continued to descend along the subduction zone." (Alvarez, l.c., p. 104).

However, the graben between the Corso-Sardinian block and the Elba ridge is certainly not the fossil trench of the subduction zone, produced by the rotation of this microcontinental plate. It belongs to a system of circum-Tyrrhenian marginal trenches (Selli and Fabri, 1971).

Another recent attempt to interpret the structural evolution of Corsica and Sardinia by means of the model of plate-tectonics is provided by Boccaletti et al. (1971). In this paper the rotation of this micro-continental "subplate" is not taken into account, for the geodynamic puzzle is approached from the side of the Northern Apennines.

The authors point out that in the E-W section across Corsica, the eastern part of the Ligurian sea and the Northern Apennines, the polarity of the overthrusting and folding movements changes from east-to-west in Corsica (western Ligurian units) to west-to-east in the Northern Apennines. The westward movements in Corsica occurred in Late Mesozoic and Early Eocene time; the eastward overthrusting and folding movements of the Northern Apennines are largely of Tertiary age.

During this structural evolution the width of the SE-part of the Ligurian basin between Corsica and Tuscany was considerably reduced, so that at present the distance between the westward directed structures on Gorgona Island (the northernmost island of the Tuscanian Archipelago) and the nearest outcrops of the eastward directed structures on the mainland is no more than about 30 km. If one tries to re-locate the Ligurian and sub-Ligurian allochthonous flysches now existent both on Corsica and on the Northern Apennines, one needs a space not smaller than 300 km. This width of the SE-part of the Ligurian Sea should have been still greater if one takes into account the oldest Ligurian sedimentary sequences ("ofiolitifero", "caotico", "argille scagliose"), aged

from Late Jurassic to Early Cretaceous (Boccaletti et al., l.c., p. 111).

Boccaletti et al. suggest that the Ligurian Sea between Corsica and the mainland of Italy was a "palaeo-ocean", which was compressed between the eastward moving sub-plate of Corsica and the westward moving sub-plate underneath the nappes of the Northern Apennines.

According to these authors the disappearance of this eastern Ligurian palaeo-ocean occurred in two phases. First the Italian sub-plate moved westward, causing an eastward plunging subduction zone; thereafter the Corsican sub-plate moved eastward, causing westward plunging subduction zones. This reversal of the polarity of the orogenic movements is an hypothesis *ad hoc*; no reasons for this reversal are suggested.

The authors, geological experts for the structural evolution of this part of the Mediterranean realm, are probably quite correct in their stating of the palimpsestic problem of the reversal of orogenic polarity and of the reduction in width of the eastern Ligurian Sea. But in stead of the geodynamic model of plate-tectonics, the model of active mantle diapirism might provide a more consistent explanation of the tectonic evolution. In the Mediterranean part of the mobile Tethys belt several centres of diastrophism were active. The Adriatic Sea is one of the older centres, which was active in Mid- to Late-Mesozoic time; whereas the Balearic centre and the centre of the western to northern Ligurian Sea are younger, having been active in Cenozoic time. The bulging up of the Adriatic tumescence occurred already in Jurassic time. This tumefaction was volumetrically compensated by the subsidence of a marginal trough, the Pennine trough of the Alps at its northern side, and the eastern Ligurian trough at its western side. Submarine extrusions of ophiolitic magma extensively covered the floor of these troughs, giving it the appearance of an oceanic crust; but these mafic crustal rocks were still underlain by the original sialic basement rocks. On top of this "para-oceanic floor" of the circum-Adriatic trough flysch of Adriatic provenance and other marine sequences were deposited. Thereafter, the buoyant asthenolithic root of the Adriatic tumescence started to mushroom and the circum-Adriatic trough was compressed and overrun by the radially outward spreading orogenic crustal

wave. This orogeny was accompanied by the northward and northwestward overthrusting of the East Alpine nappes over the recumbent fold-nappes and ophiolitic units of the Pennine structures of the Alps. Equivalent parts of the basement complex underneath the Northern Apennines moved westward over the eastern part of the Ligurian Sea, producing the westward polarity of the Alpine structural units on northern Corsica. This mechanism is illustrated by figures 4 and 5 on page 101 and 102 of van Bemelen (1972b).

The Pennine nappes and the serpentinized ophiolites acted as ball-bearings and lubricants for the gravitationally overriding crustal units of East-Alpine type. In a way the former can be considered as a shallow "subduction zone" underneath the latter. Thereafter, in Late Mesozoic and Early Cenozoic time, the centres of diastrophism in the western part of the Mediterranean became active tumefactions of the Tethys floor whilst the Adriatic tumor had collapsed. This caused the reversal of the orogenic polarity in the section under discussion. Such a model of consecutive upper mantle diapirs provides a mechanically more consistent interpretation of the intricate geodynamic puzzle of the structural evolution of Corsica and Sardinia.

It can be said that the evidence points to the view that Corsica and Sardinia indeed were situated close to the Maures and Esterel massifs of SE-France. But the original suture was situated above the present central graben of the Western Mediterranean. In the course of the Cenozoic the orogenic arcs of SE-France (Languedoc and Provence arcs) moved northwest- and northward, driven by forces emanating from the Balearic-Ligurian centre of diastrophism. Superimposed on those geodynamic processes of meso-tectonic importance there was a process of mega-tectonic importance, which pulled the entire central part of the European continent in a northwestward direction, away from the central graben system of the western Mediterranean. Corsica and Sardinia were translated in an opposite direction, eastward and also away from the central rift-graben which came into being on the crest of the Balearic-Ligurian dome. During their translation these islands rotated counter-clockwise, each around their own axis. The diastrophic evolution of the west Mediterranean centre was accompanied by radially outward

wandering crustal waves, northwestward toward the Languedoc arc, northward toward the Provence arc, and eastward toward to orogenic arc of the Northern Apennines.

The islands of Corsica and Sardinia represent remnants of the original continental crust, which formed the floor of the Tethys since the Hercynian orogeny. These islands were surf-riding on the eastward wandering crustal wave, rotating separately, but shifting sideways in combination. This lateral translation occurred not only eastward, away from the Balearic-Ligurian centre of diastrophism, but also northward, away from connecting branch between the Balearic and Tyrrhenian domes. The diastrophic evolution of the latter pushed the Corso-Sardinian block into the southern side of the Po Basin along the left strike-slip zone of Sestri-Voltaggio.

c'') The southeastward facing orogenic arc systems.

— We will now turn our attention to the orogenic arc systems which radiate from the convex side of the central graben system in east-, southeast- and southward directions. Two orogenic arc systems can be distinguished, a broad system formed by the Northern Apennines and the Tell-Atlas, which is interrupted between Rome and Tunis by the narrower system of the Southern Apennines-Calabria-Sicily.

Considering the broad system as a genetically coherent orogenic arc, one is struck by the fact that the Corso-Sardinian block occupies a position to the west of the Northern Apennines which is comparable to the structural position of the Kabyle massifs to the north of the Tell-Atlas. The Corso-Sardinian block moved eastward in the rear of the eastward migrating crustal wave of the Tell-Atlas. Both structural units represent the metamorphic continental basement complex with Cenozoic igneous intrusions and extrusions, characteristic for the inner zone of an orogenic arc. In the Kabyle massifs Mid-Cenozoic grano-dioritic batholiths are exposed, whereas in Sardinia the level of exposure is less deep, and the palaeogenic sialic magma occurs as Mid-Cenozoic ignimbrites and other volcanites of the calc-alkaline suite. The Corso-Sardinian block and the Kabyle massifs belong to the volcanic inner zone of the broad orogenic arc. They are remnants of the original continental crust, which once formed the floor of the subsiding Tethys geosyncline; this crust emerged at the end of the Meso-

zoic and the beginning of the Cenozoic as a complex system of crustal tumescences in the western Mediterranean domain.

The Northern Apennines and the Tell-Atlas represent the non-volcanic outer zone of this arc system. They are characterized by radially outward overthrust structures, the Apennines eastward and the Tell-Atlas southward. The present foredeep of the Northern Apennines in Romagna corresponds with the foredeep of the Tell-Atlas, namely the "Hautes Plaines" of Algiers.

The present foredeep of the Northern Apennines is cut off by a NW-SE trending left-lateral shearfault which separates the arc from the Adriatic basin (Fig. 4, see also Ritséma, 1969, fig. 13). Beyond the Neogene foredeep of the Tell-Atlas we find a zone of Plio-Pleistocene sedimentation and folding, 100 to 200 km wide, the Pre-Saharan Atlas which merges into the Sahara Plateau of the African shield.

The Northern Apennines are the product of an orogenic crustal wave that rolled eastward (Wunderlich, 1967) and the Tell-Atlas system was brought into existence by an orogenic crustal wave that rolled southward (Caire, 1970). Thus it appears that these two parts of the broad orogenic arc had a similar tectonic evolution, but they have different "forelands".

This broad orogenic arc system faces southeastward, embracing the Balearic and Ligurian centres of diastrophism at their southern respectively eastern sides. However, between Rome and Tunis the broad arc is interrupted by the Tyrrhenian Sea, which is — in its turn — surrounded by a narrower southeastward facing orogenic arc, composed of the Southern Apennines, Calabria, and Sicily. This narrow arc system developed also as an orogenic crustal wave, which spread radially outward from the Tyrrhenian centre (Caire, l.c.). The diastrophic pulsations of the Tyrrhenian centre began also already at the end of the Mesozoic, but its orogeny differs from the evolution of the broad orogenic arc system in the fact that it is still active in the Calabrian apex of the arc. Moreover, the inner zone, consisting of basement complex rocks from the centre, has been thrust ESEward over the outer zone, now forming the great Peloritanean nappe of Calabria and NE-Sicily.

The "foreland" of the Tyrrhenian arc has also a different character in the various sections, being

formed by the Adriatic Basin and the crustal blocks of Monte Gargano and Apulia to the NE of the Southern Apennines, the Ionian Basin to the east of Calabria, the Ragusa block to the south of the Sicilian section, whilst the young Maltese Basin disrupts the ward.

The Alpine type of orogeny in the western Mediterranean area consistently shows this pattern of structural evolution.

Three focal centres of orogeny can be distinguished, (1) the Alboran centre surrounded by the orogenic arc of the Rif-Betic Cordillera, (2) the Balearic-Ligurian centre surrounded at its south-eastern side by the orogenic arc of the Northern Apennines and the Tell-Atlas system of Algeria, (3) the Tyrrhenian centre surrounded at its south-eastern side by the Southern Apennines, Calabria and Sicily (see fig. 3). All these parts of the alpine orogenic system spread radially outward from centres of diastrophism inside the realm of the Tethys geosyncline. These centres emerged, producing an extensive land area. The land in the western Mediterranean is called by Caire the "Sardinian Province". This land collapsed and it was transformed in the course of the younger Cenozoic into the present intercontinental sea basins of the western Mediterranean. These collapses of the crustal domes were accompanied by intensive volcanic activity; the centres were typical "hot spots" according to the jargon of modern geophysicists. The pre-Mesozoic continental crust, originally occurring at the base of the Tethyan geosynclinal sequences, reappeared in the complex of Lower- to Mid-Cenozoic domes of the Sardinian province, but it appears that after the Young-Cenozoic collapse of these domes, now forming the Mediterranean sea-basins, the continental type of crust had changed into a crust with a composition and thickness intermediary between typical continental and typical oceanic crusts. The micro-continental Corso-Sardinian block is merely a remnant of this original continental crust of "Tethyca" (van Bemmelen, 1972). Also this geochemical crustal transformation has to be explained by the geodynamic models of interpretation.

The Ionian-Adriatic-Po Basin is an older Mediterranean centre of diastrophism, which developed already since the Jurassic (pre-Gosau). Trümpy (1971) compares the deep Jurassic troughs of the classical Alps in central Europe with the other deep

collapse basins of the present Mediterranean Sea. Trümpy's stratigraphical studies of the Alps lead him to the acceptance of the concept of oceanization by replacement of the lower part of the continental basement of the Tethys geosyncline by denser material. This process has been called the "Mediterranean type of oceanization" by the present author (van Bemmelé, 1969).

This process of oceanization was active in the Ionian-Adriatic-Po centre of diastrophism, which emerged in mid-Mesozoic time and produced the great northward overthrusts of the Eastalpine Nappes; thereafter it collapsed, whilst the Alpine orogenic wave rolled northward (Wunderlich, 1967). The collapse of this centre created the "back deep" of the Alps. This oceanization gave free board to the Cenozoic orogenic crustal waves which, thereafter, spread eastward from the Balearic-Ligurian and Tyrrhenian centres, producing the Apennines, and westward from the Pannonian centre, producing the Dinarides. This result of the relativistic structural analysis of the Cenozoic orogeny in the central Mediterranean area gives a solution for the jig-saw puzzle of the displacements in time of the structural units, with different bearings and amounts of lateral shift.

The general picture of the Alpine type of orogeny in the Mediterranean area indicates that its driving forces are to be sought at the concave inner side of the orogenic arcs, and that the orogeny occur independent from the "foreland". — The orogenic crustal waves spread from centres of diastrophism in which the original sialic continental crust is being reduced in thickness (or eventually entirely removed, as locally in the Ligurian Sea). The oceanization of the centres of diastrophism occurred by magmatic (geochemical) processes, emanating from the upper mantle, and corroding the lower side of the crust, locally invading shallower crustal levels as grano-dioritic plutonic masses (batholiths), and eventually reaching the surface as external volcanic activity of largely calc-alkaline and partly sub-silicated hybrid magmas. Basaltic magmas of deeper provenance (from the upper mantle) occasionally also reach the surface, e.g. the Stromboli volcano. The reduction of the sialic crust by subcrust-connection with the Berberides.

The Upper-Cenozoic Maltese basin of subsidence is a mobile crustal stretch, characterized by NE-SW

trending fold-axes along its margins and the NW-SE directed Maltese tensional graben in its centre. The tensional movements are accompanied by volcanic activity. The extinct-volcanic islands of Pantelleria and Linosa lie inside the graben, whilst the NW-SE normal (tensional) faults which separate the graben from Sicily form a band of submarine eruptions, called the "Campi Flegrei del mar di Sicilia" (Imbò, 1965; Neumann van Padang, 1938).

Cairé (l.c.) compares the fundamental processes of the orogenic evolution of Sicily with the movements of the sea, distinguishing several rheological processes which acted separately, partly simultaneously and partly at different times. The effects of these geodynamic processes are superimposed on each other, producing the present structural features. He distinguishes (a) an "orogenic swell", comparable to an oscillating, standing wave, (b) an "orogenic wave", which migrated radially outward, and (c) the "breakers" which originated by the tearing off and scattering of the crests of the orogenic wave, comparable to the breakers of sea waves which topple over on approaching the strand (c.q. the "foreland").

It goes without saying that these comparisons are only descriptive models, which can not serve as interpretations of the mechanism of tectogenesis. Nevertheless, the description of the Tyrrhenian orogeny by this great contemporary specialist of the geology of this part of the Mediterranean leads to a general geodynamic picture which closely resembles that of the undation theory, which was applied by the present author to the Mediterranean almost four decades ago (van Bemmelé, 1933).

d) Some general aspects, derived from the evidence

In the foregoing pages some results of recent researches in the fields of marine geology, geophysics and land geology have been discussed. It is of course impossible to give an exhaustive account of the overwhelmingly great amount of diagnostic facts concerning the geonomy of the Mediterranean seas and the Alpine mountain system in this area, gathered by several generations of earth-scientists. The memory of the greatest computer would be incapable of comprising them all.

Therefore, the scientific procedure is to boil down the fundamental facts of observation to more general views and rules, which can be manipulated more

easily by our thinking. Of course such contractions are no longer hard facts; they are tentative suppositions (inductions) which should always be open for renewed verification in the light of further and/or other evidence. Geodynamic models are still more synthetic views, generalizations based on the more elementary contractions of the basic facts of observation. They are merely mental images of the structural evolution of the earth's crust. We may call them functionally correct models when their rational expectations (deductions) are conform to the available evidence. Such correct models on our geonomic environment help us to realize our place and our possibilities in an evolving cosmic system. In order to have such a pragmatic value, the suggested geodynamic models have to be tested by the prognosis-diagnosis method of scientific verification.

In the next chapter three geodynamic models will be discussed in the light of the evidence provided by the Tyrrhenian test-case. But before doing so, this chapter will be concluded by drafting some tentative views and rules, to which the available geonomic evidence on the Mediterranean orogeny seems to point (see also v a n B e m m e l e n, 1972c).

One result of Caire's analysis of the structural evolution of Sicily and its Mediterranean frame stands out clearly:

The driving forces of the regional Alpine orogeny are directed radially outward from the Tyrrhenian centre of diastrophism. — This Tyrrhenian centre showed, since the end of the Mesozoic, pulses of uplift, causing crustal domes surrounded by (volumetrically compensatory) belts of subsidence. The phases of doming alternated with periods of quiet descent and/or erosion of the tumescence. Caire compares this persistent tendency for rise in one area and subsidence in a marginal belt with an standing wave of the sea, an "orogenic swell". In later stages of the structural evolution the central tumefaction of the crust collapses whilst an "orogenic wave" spreads radially outward.

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The crustal thickness of the central domes is also reduced at its upper side. This removal of crustal material can occur in two ways, (1) by crustal spreading and (2) by erosion.

(1) The crustal spreading produced nappes of the East-Alpine type. In the Tyrrhenian test-case the Panormide and Peloritian nappes of Sicily and Calabria represent this type of spreading. The basement complex in these Tyrrhenian nappes is largely of Paleozoic age and in an epimetamorphic (shallow) state. These basement rocks are partly imbricated and alternate with Mesozoic to Lower-Cenozoic limestone ranges in NE-Sicily. Evidently these nappes are derived from the uppermost part of the crust.

(2) The erosion produced detrital sediments of flyschlike and molassic character in the marginal depressions around the central dome. These sediments contain many sedimentary Klippes derived from the Mesozoic cover of the central Tyrrhenian dome; the quartz-grains in the Numidian flysch are derived from Verrucano-like Permo-Triassic sediments in the Balearic and Tyrrhenian province (Sardinian province), as has been proven by thermoluminescence investigations (C a i r e and C o i f f a i t, 1970). These observations indicate that the removal of matter from the top part of the Tyrrhenian dome did not penetrate deeply down into the sialic continental crust. The process of denudation was restricted to a removal of the epidermal skin of post-Hercynian sediments and the epimetamorphic Hercynian basement complex. A safe estimate is that not more than about 5 km of the basement complex were removed by erosion and spreading at the top of the dome.

On the other hand, geophysical researches indicate that the original continental crust of the Sardinian province has been reduced to an intermediary crust, which has only one third of its original thickness. This means that about half of the original continental crust was removed from its base by a major geochemical process of subcrustal corrosion presumably by overheated basalt magmas ascending from the mantle, to the asthenosphere).

Concluding these remarks, it can be said that the Alpine orogeny in the Tyrrhenian test case is characterized by three major aspects:

- 1) *The orogeny started with the doming up of the floor of the Tethys geosyncline in the Tyrrhenian centre of diastrophism.* From Late-Cretaceous to Mid-Pliocene time this dome was subjected to pulses of uplift, alternating with periods of quiet subsidence. In Mid-Pliocene time the Tyrrhenian centre still had the aspect of the Cyclad archipelago in the Aegean area, namely submerging islands, separated by shallow sea-channels and sounds. Since then it subsided at a rate of 1 mm/yr, and it now forms a bathyal basin of three to four kilometers depth.
- 2) *During its geodynamic evolution the central dome was subjected to igneous intrusions and extrusions, and reduction of the crustal thickness.* The continental type of crust, which had come into existence since the Hercynian orogeny, has been transformed in the course of the process of alpine diastrophism into an

intermediary type of crust of 11 to 12 km thickness. The underlying asthenosphere is at present crowned by a bulge of ultra-low velocity of seismic shear waves, rising to about 60 km below the surface. These observations indicate that *the crustal transformation resulted not only from erosion and spreading under gravity at its top, but it was in the first place a major geochemical process, which removed some 15 to 20 km of sialic crustal matter from the base of the original crust by a kind of subcrustal corrosion.*

3) Apart from the spreading under gravity of the top part of the Tyrrhenian dome, *the circum-Tyrrhenian orogeny sensu stricto was characterized by a radially outward migrating crustal wave during the Mid- and Upper-Cenozoic.*

C. THREE MODELS OF INTERPRETATION

After the foregoing review of some recent geonomic researches in the Tyrrhenian domain, and the formulation of some characteristic aspects of the Alpine orogeny in the Mediterranean area, based on observational evidence, three models for the interpretation of the geodynamic evolution of the Tyrrhenian test-case will be discussed in this chapter.

Model I: *Plate tectonics*

The model of plate tectonics is a geo-mechanical way of interpreting the process of orogeny as the boundary effects between colliding lithospheric plates. The plates move away from mid-oceanic rift belts, where new oceanic crust is formed and sea-floor spreading occurs. The lithospheric plates are hampered in their lateral movements by adjacent plates. The resulting space problem is solved by compressive tectonics causing an increase of crustal thickness, and/or by "subduction zones", in which a plate is thrust under the margin of its neighbouring plate. Such compressive subduction is accompanied by the formation of marginal deep-sea trenches and by seismic activity of the so called "Benioff Zones" of the underthrusting plate, showing earthquakes with foci at normal, intermediate and great depths.

In the Tyrrhenian area earthquakes occur at normal, intermediate and even great depth. This seismicity has been interpreted as the effect of the underthrusting of the African plate underneath the European one (f.i. Caputo et al. 1969; Allan and

Morelli, 1971; Hays and Ninkovitch, 1972). Ritsema (1970) published a tentative WNW-ESE section across the Tyrrhenian, illustrating the application of plate tectonics to this area (fig. 5).

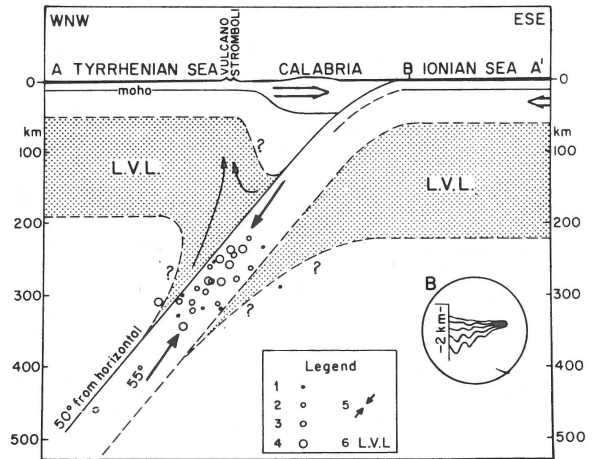


Fig. 5
WNW-ESE section across the Tyrrhenian orogenic system, interpreted according the geodynamic model of plate tectonics as suggested by Ritsema (1970).

There are some fundamental discrepancies between the expectations (prognoses) of the model of plate tectonics and the observational evidence (the diagnostic facts). In the first place there is a contrast between the steady rate of movement of the plates, according the observations on sea-floor spreading (plate-movements, which are considered to be the driving force of the marginal diastrophism), and the episodic character of orogeny. How are the compressive stresses between colliding plates stored, so that they can be released in a more spasmodic rhythm? In view of the small compressibility of the rocks this question can only be answered by means of complicated *ad hoc* hypotheses (see, for instance, Dickinson and Luth, 1971; Mc Birney, 1971; Peter J. Smith, 1971).

McKenzie (1970, 1972) distinguishes in the eastern part of the Mediterranean area two smaller, rapidly moving continental plates (Eastern Turkey and the Aegean subplates) which shift west-respectively southwestward, toward the Ionian basin. These subplates apparently move independantly from the

northward pushing African plate, so that the latter cannot be their driving force. The Aegean subplate is bordered at its southwestern side by the Hellenic-Cretan orogenic arc with its foredeep. At the western side of the Ionian basin we find the Tyrrhenian orogenic arc which spreads ESE-ward toward the Ionian basin. Consequently the Ionian basin is being narrowed by simultaneous orogenic movements from NE to SW and from WNW to the ESE. It is a contracting basin, and this contraction cannot be caused by northward movements of the African plate. R i t s e m a (1972) also states emphatically that it is a mechanical impossibility that in the present time the African plate causes compression in two directions at right mutual angles, northeastward toward the Aegean subplate and northwestward towards the Tyrrhenian subplate.

Moreover, it seems impossible to explain the complexity of some 100 million years of episodic orogeny of the Alpine system in the Mediterranean area by the steadily underthrusting of the African plate.

At the annual meeting of the GSA at Washington D.C., November 1971, a fervent protagonist of plate tectonics, said that the "marching northward" of the African plate toward Europe caused the elevation of the Gibraltar arc, separating the Mediterranean basin from the Atlantic ocean and starting the Late-Miocene desiccation of the former, with evaporites formed by the crisis of salinity during the Messinian (H s ü, 1971). A more technically minded geoscientist might ask: "Why should we use a bulldozer to lift up a small lump of earth? So why should we suggest a persistent northward displacement of a major global plate, Africa, to explain the episodic rise of a small rock-unit at its margin?"

The same speaker advanced another argument for the northward underthrusting of the African plate based on the results of the drilling at site 127 of leg 13 of the Deep Sea Drilling Project. This site is situated in the foredeep of the Hellenic-Cretan orogenic arc; the drill penetrated some eight meters of Lower-Cretaceous limestones, which directly overly soft Pliocene oozes. This situation is interpreted as the effect of the northward subduction of the African plate. However, this mechanical interpretation is a gross over-estimation of the draught and the extent of this abnormal stratigraphical succession.

It is more realistic to interpret this situation as

the result of a local gravity slide, which occurred from the front of the rising Hellenic-Cretan orogenic arc into its subsiding foredeep (v a n B e m m e l e n, 1972c).

Yet another, more indirect though severe, objection to the application of the concept of plate tectonics to the Tyrrhenian test-case is provided by the modern seismic researches. In the sections across the Tyrrhenian area, for instance those published by C a p u t o et al. (1969) and R i t s e m a (1970), the rigid African plate is supposed to underthrust the European lithosphere to a depth of some 500 km. One might expect that earthquakes occur all over the Benioff zone of this underthrusting plate. However, there is a significant gap in the foci between 110 and 220 km depth, exactly at the depth of the asthenosphere. Apparently the asthenosphere stretches continuously from the Ionian to the Tyrrhenian area, and it is not interrupted by a traversing stiff plate.

The application of the geodynamic model of plate movements to the paleomagnetic evidence in the western Mediterranean is attempted in a recent paper by V o g t et al. (1971). These authors discuss the counterclockwise rotations of smaller blocks with a continental type of crust in the western Mediterranean area. These rotations are established by the paleomagnetic researches of the school of Utrecht. V o g t et al. constructed a map with a mozaic of rotating blocks which cause fan-like spreading of the floor in the basins in the western Mediterranean (fig. 6). However, several serious objections can be advanced against such a synthesis of the observational evidence.

First of all, the counterclockwise rotations of Spain, Corsica-Sardinia, and Italy are not synchronous structural processes, which can be interpreted as a ball-bearing mechanism between the European plate and the relatively eastward moving African plate. The rotation of the Iberian block occurred between the Triassic and the Upper Cretaceous (v a n d e r V o o, 1969; v a n d e r V o o and Z i j d e r v e l d, 1971). The rotation of Sardinia occurred in Cenozoic time (d e J o n g et al., 1969), and its eastward translation may proceed to more recent times (A l v a r e z, 1971, 1972; see also chapter B section c' of the present paper). Evidently the expectation of simultaneous rotations according to a kind of "ball-bearing" mechanism between the European and African

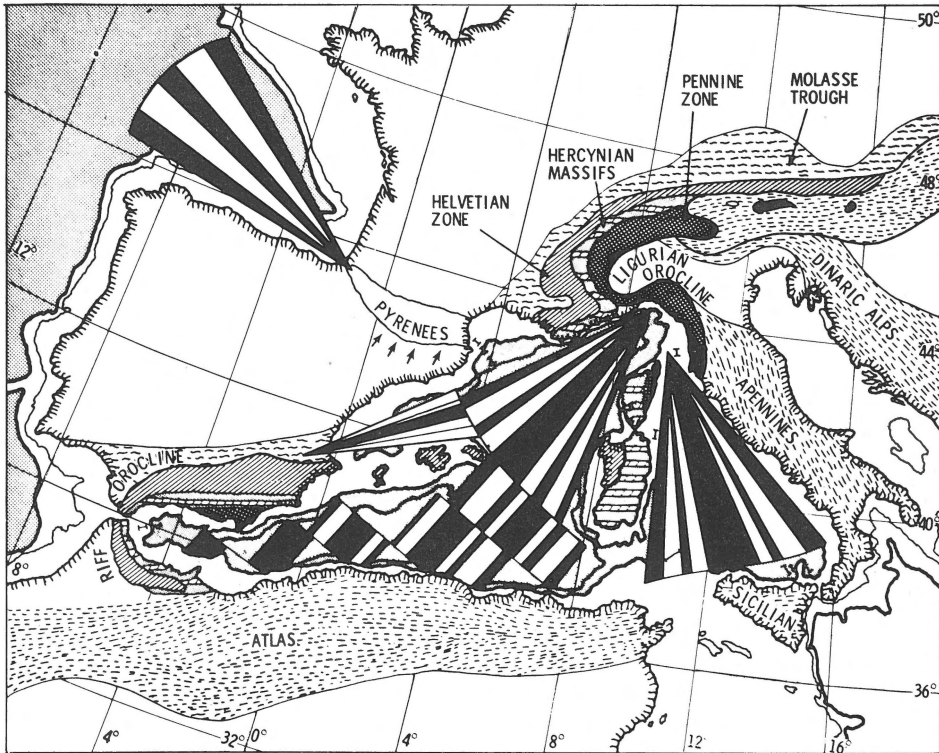


Fig. 6

Rotating blocks and sea-floor spreading in the western Mediterranean area, according to Vogt, Higgs, and Johnson (1971).

plates is not confirmed by the paleomagnetic observations.

Secondly, the rotations of the blocks in the western Mediterranean according to Vogt et al. would cause NW-SE trending left strike slip faults. This prognosis comes into conflict with the structural pattern of the northern margin of the African plate, where NE-SW shear-faults prevail.

Thirdly, the mechanism of counterclockwise rotating blocks as ball-bearings between the European and African plates leads to the prognosis that Africa moved eastward with respect to Europe. The observations indicate, however, that there were westward movements in Permo-Triassic time (de Jong, 1966; van Bemmel, 1970a, and 1972b), and that in the present time the relative movements of Africa are also westward (see Ritsema's seismic analysis, 1969).

The geological evidence seems to point to a westward translation of Africa with respect to Eurasia along the Tethyan shear zone in the past, and the seismic evidence indicates similar relative movements in the present. Such mega-tectonic movements will have a tendency to be consistent in time. The directions of continental drift will only change slowly and gradually. Africa can not be shoved around at will, once eastward, once westward, once northward, as is suggested by Smith (1971) and Hsü (1971) in their attempts to explain the Alpine orogeny by plate tectonics. Africa is not a matchbox which can be pushed in any direction over the surface of a table; it has to fit into the general process of relative mutual displacements of structural units over the global surface in the course of the earth's geodynamic evolution.

The various models of plate tectonics, advanced as

explanations of the Alpine orogeny in the Mediterranean area, (such as Smith, 1971) are characterized by the fact that they start with the model and then proceed with a selective (eclectic) supply of data which might be explained by the model. This seems to lead to impressive results. But such a procedure neglects by far the greatest part of our geonomic knowledge about the origin of the Alpine mountain system.

A more correct procedure would be to start with the diagnostic facts themselves, which are then organized inductively into more general views and rules. Thereafter the deductions from a covering synthesis, such as the geodynamic model of plate tectonics, can be tested by means of the prognosis-diagnosis method of verification.

Other examples of the interpretation of the geodynamic evolution of the Mediterranean by means of plate tectonics might be critically discussed (for instance Andrieux et al., 1971, on the western end of the Mediterranean, and McKenzie, 1972, on the eastern end).

The above examples may suffice to show that the available data are either forcefully adjusted to this model of interpretation or they are entirely neglected. In this way *the mode of plate tectonics deteriorates into a procrusteanization of the available evidence; instead of accepting the conclusion that the discrepancies between the expectancies (prognoses) of this model of interpretation and the diagnostic facts call for a fundamental revision of the model itself.*

Model II. Crustal radioactive heating

Schuiling (1969, 1972) proposes a geothermal model for the driving forces of orogeny, and applies it also to the orogenic arcs of the Mediterranean area.

This model is based on the fact that most of the continental heatflow is produced by radioactivity in the "granitic" crust itself, which acts as a "thermal blanket" over the mantle. The model suggests that unequal heating underneath continents and oceans will periodically cause continental drift (plate tectonics) with linear mountain belts formed by compressive tectonics along the margins of colliding lithospheric shields. The entire present situation, which shows that the asthenosphere under the oceans has a shallower position than under the continents, is declared

to be an abnormality resulting from the previous period of worldwide continental drift. According to Schuiling the situation should be the reverse, namely shallower under the continents and deeper under the oceans. Owing to the heating by the continental thermal blanket the underlying asthenospheric layer will again become shallower under continents than under the oceans. Then a new gravitational instability would have been created, and continental fragments will slide downslope over the oceanward descending top of the asthenosphere. The periodicity of this sliding to and fro of continents, resulting from their heating of the underlying mantle, is estimated to be of the order of 240 million years.

We will refrain from discussing this daring hypothesis on the origin of mega-tectonics and concentrate our discussion on the application of this geothermal model to the orogeny in the Mediterranean.

The radioactive heating inside the sialic crust is of course a fact which has to be taken into account, and it is necessary to estimate the importance of this energy source for orogeny. The huge Andean and Cordilleran batholiths along the western margin of the American continental shields may have been partly or entirely the result of radioactive heating of a thickened granitic crust, which caused melting and the ascent of plutonic masses. Volume changes by the heating and subsequent cooling will cause oscillatory movements of the surface, accompanied by changes in the field of potential gravitational energy, by erosion and sedimentation.

Schuiling's geothermal model bears some resemblance to ideas forwarded by Hsü (1965). Both authors suppose that landmasses can disappear by supracrustal erosion of crustal bulges created by radioactive heating, and that these bulges thereafter collapse as the result of cooling.

Trümpy (1971, p. 308-309) remarks that application of this concept to the Alpine type of orogeny encounters a number of difficulties, though it might explain the subsidence of the Paris basin after the strong erosion it underwent during the Lower Triassic.

Schuiling remarks that colliding plates will cause linear mountain belts, where the crust is thickened by compressive tectonics. The greater radioactive heating by such linear orogenic belts is still more invigorated in bended parts, where a focal concentration of the

radioactive heating at the concave inner part of the bend is to be expected. He calls such focal areas of heating "orogenic nodes". The heating of the crust and the underlying mantle will cause crustal bulges during later stages of the orogenic evolution, underlain by molten blisters.

However, this expectation of the model of crustal heating is not confirmed by observational evidence. The straight stretches of the central and eastern Alps and of the Tellian Atlas show pulses of orogenic evolution of similar ages as those of the more curved sections around the orogenic nodes. The Oligo-Miocene Numidian flysch sediments were deposited in a continuous ring-depression at the southern side of the emergent landmasses of the Balearic and Tyrrhenian centres of diastrophism. The Mediterranean centres of orogeny show differences in the times of their incipience and the present state of their evolution; but the foregoing quotations from *C a i r e* (1970) show that these differences of the age of the tectonic periods are not dependant on the straight or curved form of the mountain belts.

Another objection against *Schuiling's* model of geothermal blisters at the concave side of orogenic arcs is the fact that this model envisages only vertical oscillations of the crust; namely a central dome and a single ring-depression ("foredeep"). The structural evolution of such centres of orogeny, however, shows that they are characterized by crustal waves, which spread radially outward from the collapsing central bulges. Such migrating orogenic arcs differentiate into volcanic inner zones and non-volcanic outer-arcs with radially outward directed overthrusts. The orogenic "drama", as it is called by *H e n r i* and *G e n e v i è v e T e r m i e r* (1957), is a much more complicated geochemical and structural process than the mere up and down movements of the crust owing to the changes of volume and density caused by radioactive heating and subsequent cooling, which is accompanied by supra-crustal erosion and sedimentation.

As type-locality for the thermal node model *Schuiling* discusses the Aegean area, with the Cyclad islands at the centre. During the Cenozoic this Cycladian centre has been subjected to a series of pulses of uplift, alternating with periods of quiet subsidence. Some remnants of marine Eocene sediments on the deeply eroded basement complex date the beginning

of the orogenic cycle in this central area ("Internides") as Late Mesozoic. From the Internides crustal waves migrated south- and southwestward, now forming the "Externides". The latter consist of a volcanic inner arc with the famous Santorin (Thera) volcano, a non-volcanic outer arc with the island of Crete, and a foredeep around the Hellenic-Cretan arc. This outward wandering of the orogenic wave system has been summarized by *G o d f r i a u x* (1968). The geological analysis of this peri-Aegean system clearly shows that it was a southward facing orogenic arc from the onset and not a more straight mountain belt which was curved afterwards forming a thermal node at its Cycladian centre.

M c K e n z i e (1972) recently also applied the model of plate tectonics to this Aegean orogenic system, suggesting that it was originally a more straight belt which was deformed into an arc in the course of the Cenozoic. But such palinspastic reconstructions are not conform the evidence that the orogenic arcs of the Alpine mountain system in the Mediterranean are spreading like waves from centres of diastrophism, thus being arcuate from the onset.

As concluding remarks on the model of radioactive crustal heating the following might be said: For the understanding of the driving forces of orogeny it is of course necessary to investigate the possible effects of radioactive heat development in the crust. But this heating process is not a closed system. In the course of the tens of millions of years of its cycle it meets with cross-roads and counter-effects of other processes, such as mass-circuits in the mantle and irreversible geochemical processes, which may become more dominant for the orogenic evolution.

The geodynamic evolution of the earth in the course of billions of years resulted from the liberation of endogenic free energy. In this general evolutionary process the radioactive heating of the continental crust (*Schuiling's* granitic "thermal blanket") is a *feed-back mechanism*. Therefore, the orogenic effects of the thermal blanket is merely a complication of the main process of diastrophism, and can not represent the ultimate main source of the driving forces of orogeny.

Consumption of this sialic blanket by subduction according to the model of plate tectonics (model I) or by the process of Mediterranean type of oceanization (model III, to be discussed hereafter) would be pos-

sible ways of recycling the radiogenic heat sources to greater depths in the mantle. It would be interesting to study the thermal consequences of such consumption of the granitic crust, and to compare the prognoses of these calculations with the diagnostic data of heat flow. Perhaps this would provide means of verifying the functional correctness of various geodynamic models.

Model III: Mantle diapirism

The model of active mantle diapirism at the concave inner side of orogenic arcs is advocated by the present author. According to this model the driving forces of orogeny act radially outward from centres of diastrophism. The first application of the "undation theory" to the Mediterranean was published in 1933 and the latest elaboration for the Tyrrhenian testcase is given in chapter VIII of "Geodynamic models" (van Bemmelen, 1972b). For the sake of shortness we may refer to the latter discussion. The present paper gives a new WNW-ESE section through the Tyrrhenian basin across Calabria to the Ionian basin (fig. 7);

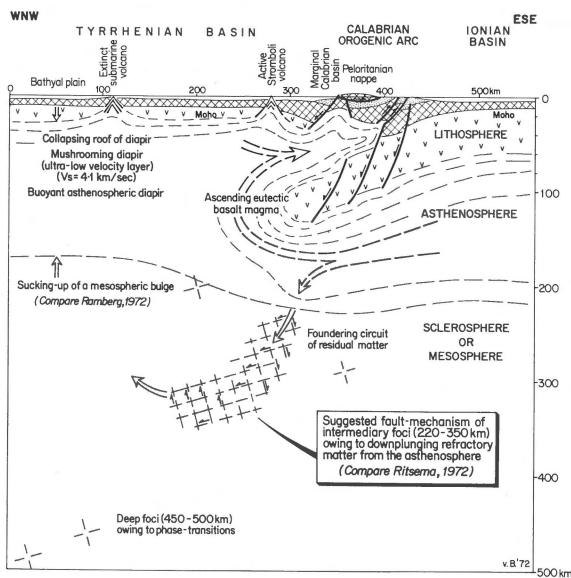


Fig. 7
WNW-ESE section across the Tyrrhenian orogenic system, interpreted according to the geodynamic model of active mantle diapirism.

The main feature of this section is, that it illustrates the driving forces of orogeny as the effect of a

mantle diapir, rising from the asthenosphere because of the buoyancy of segregated basaltic melts. This diapir first caused the bulging up of the Tyrrhenian centre of diastrophism. The doming is followed by collapse owing to the mushrooming of the top of the asthenolith which was squeezed sideward between the load of the cooling and crystallizing roof and the buoyant main body of the asthenolith.

This process of active mantle diapirism can explain the entire range of geonomic evidence for the structural evolution of this area, as well as its geochemical evolution, namely the transformation of the originally normal continental (sialic) crust into an intermediary type of crust, by means of some kind of subcrustal corrosion. The present author suggests the following process. The buoyant diapir of the asthenosphere consists of a mixture of basalt magma and crystalline upper mantle material. On reaching the base of the continental crust (the continental Moho), the overheated basaltmagma will produce palingenic sialic melts and a mixture of simatic and sialic melts comes into being, which may rise still higher into the crust as long as its density is still lower than that of the surrounding crust. However, after a phase of plutonic intrusions and possibly also volcanic activity at the surface, cooling will prevail causing crystallization of the asthenolithic roof and its intrusive offshoots, so that the mean density rises considerably. An inversion of the stable density stratification will result, leading to dislodging of crystalline masses with a relatively high density from the roof by means of a process of overhead stoping. These heavy dislodged masses will fall straight down through the hot and partly molten asthenolith. They may subside even further into the underlying mesosphere, until these mixtures of sialic and simatic matter come to rest in the state of high-density and high-temperature mineral phases. But it seems more probable that the subsiding blocks of mantle-crust mixture will also be partly recooked, again splitting up into refractory matter and palingenic melts. The latter will be taken up by the buoyant flows inside the mantle diapir. Such smaller convection currents, resulting from complex physico-chemical reactions between foundering blocks and rising melts, can be compared with the mixing processes going on inside active conduits of volcanoes.

Mantle diapirs are about a hundred times greater

than intra-crustal sub-volcanic diapirs, and their geochemical effects will be much more vigorous and more complex than those which can be studied more closely in relation with surface volcanism.

The smaller circuits of matter inside the mantle diapir are not indicated in figure 7 for the sake of clarity of the drawing. This section only illustrates the two major circuits of matter occurring in relation with mantle diapirism. These circuits result from the segregation of eutectic basaltic melt from the original matter in the asthenosphere. The eutectic melts will accumulate upward and the refractory residues downward, so that in centres of diastrophism a splitting up of the asthenosphere results. The buoyant upper part

rises diapirically upward as an ultra-low-velocity-channel, causing the chain of geodynamic events which can be studied at the surface, and which are accompanied by normal, intra-crustal seismicity, occurring for the greater part in the orogenic arc, whereas the foundering lower part plunges downward into the mesosphere, causing earthquakes at intermediary depths underneath the Tyrrhenian basin. The downward flow may also trigger earthquakes caused by phase-transitions at still greater depths, such as the two shocks at about 450 km depth, observed underneath the Tyrrhenian basin.

The focal fault-mechanism of the intermediary shocks is orientated as indicated in the section,

TABLE I

Comparison of the characteristic features of the three models, advanced for the explanation of Mediterranean orogeny.

Type of model	Model I: Plate tectonics	Model II: Radiogenic heating by the continental crust	Model III: Mantle diapirism
Characteristic features			
Character of the driving force	Geomechanical	Geothermal	Geochemical
Character of the equilibrium process	Collision between the African and European lithospheric plates	"Feed back" of radiogenic heat from the granitic (continental type of) crust; "thermal blanket" concept; formation of geothermal blisters.	Segregation of basaltic magma from the asthenosphere, causing tumescent centres of diastrophism in the Tethys belt.
Primary direction of the tectonic stresses in the lithosphere.	Horizontal and subparallel, from the front of the African plate toward the convex side of the Mediterranean orogenic arcs.	Vertical crustal oscillations at the concave side of the orogenic arcs.	First vertical doming up of the crust in centres of diastrophism; then collapse and radially outward spreading crustal waves (mushrooming mantle diapirs).
Main processes of crustal removal	Consumption of the African plate by the upper mantle <i>after</i> its subduction.	Supra-crustal erosion during doming of crust over geothermal blisters.	Supra-crustal tectonic décollements and erosion; intracrustal spreading under gravity; subcrustal corrosion by geochemically active (asthenolitic) diapirs.
Result of testing by the prognosis-diagnosis method of verification.	Explains neither the crustal transformations in the Mediterranean seabasins, nor the lateral spreading of crustal waves.	Does not explain the spreading of orogenic crustal waves from the collapsing domes over the geothermal blisters.	Explains coherently the initial doming of centres of diastrophism and their ultimate collapse, accompanied by outward spreading crustal waves, as well as the volcanological and geophysical evidence.

according to Ritsenma (1969). There are four possible faultplane solutions, if we take into consideration that only one block is displaced in relation to the surrounding matter of the mantle. It is suggested that in the various foci alternatively different relative displacements are realized, as indicated in figure 7. At the top of the cluster of shocks at intermediate depths a downward compression may occur, caused by a major stress exerted by refractory matter plunging into the mesosphere WNW-ward at an angle of about 60° with the surface. But at the base of the cluster the relative displacements of blocks will be influenced by a circuit of matter in the mesosphere, which occurs as the result of its sucking up underneath the buoyant part of the mantle diapir. The mechanism of sucking up is clearly illustrated by Ramberg's centrifuged experiments (1972). It causes a sideward extension of the cluster and a westward curvature of the pearshaped form.

D. CONCLUSION

After this short review of the three models which have recently been advanced for the explanation of the Mediterranean orogeny, it can be concluded that the third model, that of active mantle diapirism, appears to be functionally correct in view of the available evidence. This result is summarized in Table I.

Of course model III is but a tentative working hypothesis, and further data may necessitate readjustments and elaborations of the model according to the observations. However, because this model is based on scientifically sound principles it has a great adaptability, without becoming a "Procrustes-bed" for the diagnostic facts (van Bemmelen, 1972c).

If it is accepted as a functionally correct concept for the explanation of the Mediterranean orogeny, then the idea of geochemically active mantle diapirism has far-reaching consequences for our understanding of orogeny and other geodynamic processes elsewhere on earth. The present author has tried to trace and to outline these consequences in "Geodynamic models" (1972b).

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