OROGENY AND OPHIOLITES: PLATE TECTONICS REVISITED WITH REFERENCE TO THE ALPS[1]

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ABSTRACT

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We develop a geodynamic scenario that explains many features of Alpine orogeny and ophiolite thrust sheet emplacement. Important elements of this scheme are: 1. age-dependent subduction and a related compressive regime upon the closing of small and young oceanic basins. 2. the induction of thermal upper mantle anomalies by spreading and lithospheric doubling and subsequent apparent migration by lithospheric shifting. It is shown that these processes, which have hitherto not been taken into account in intra-continental tectonics, play a crucial role in mountain building. This applies in particular to their function in gravity tectonics, metamorphosis and post-orogenic epeirogenesis and foreland uplift.

INTRODUCTION

Plate tectonic theory has proved to be fundamental for our understanding of the evolution of oceanic lithosphere. Aplying plate tectonic concepts to orogeny, however, has up till now merely resulted in partly conflicting mechanisms of varying degree of complexity, which have deferred to the present an understanding complying with present-day available geological and geophysical data (e.g. SMITH & WOODCOCK, 1982). Geological evidence is accumulating (e.g. TRÜMPY, 1982) that the genesis of fold belts takes place in a setting that does not conform to the standard concepts of plate tectonic subduction and kinematics. In particular the notion that small sedimentary basins created in an overall transcurrent and extensional regime are precursory to folding and thrusting, is becoming increasingly important (ZWART & DORNSIEPEN, 1978). The closing of these small ocean basins is assumed to lead to the formation of fold belts. The closing of a small ocean basin, however, may involve the subduction of young oceanic lithosphere and even of spreading ridge segments. The consequences of this observation have not yet been exploited in models for orogenic processes.

We address the problem of the emplacement of ophiolite nappes in Alpine fold belts. Ophiolites are tectonic emplacements of former segments of oceanic crust (DE ROEVER, 1957), created at spreading centres (ANDERSON ET AL., 1982). Geological evidence of long standing suggests that both compressional and gravitational agents are involved in nappe tectonics. However, the plate tectonics theory as it stands today does not provide for differential vertical displacements of sufficient magnitude in an intracratonic setting. Gravity tectonics, an otherwise adequate mechanism for gravity sliding, is, therefore, usually rejected. As far as compression, which leads to crustal shortening, is concerned, it is not clear whether that is the primary deforming agent or merely the consequence of gravity tectonics.

UYEDA & MIYASHIRO (1974) and VLAAR (1975), independently and on different grounds have suggested the possible significance of the age of oceanic lithosphere for its subduction behaviour. VLAAR & WORTEL (1976), WORTEL & VLAAR (1978) and WORTEL (1980) have quantitatively demonstrated that lithospheric age is the key parameter governing the subduction process. CLOETINGH (1982) and CLOETINGH ET AL. (1983, in press.) studied the mechanics of the transformation of passive into active margins. Their results quantified the effectiveness of closure of young and presumably small oceanic basins. VLAAR (1982, 1983a, b) investigated some thermal, magmatic and geophysical consequences of lithospheric doubling ('subduction' of young oceanic lithosphere and ridge segments)

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and introduced the concept of lithospheric shifting.

In this paper we include these concepts in plate tectonic theory and propose that they may be crucial for understanding mountain building, at the same time reconciliating the standpoints of compressional and gravitational tectonics.

One of us (N.J.V.) wishes to express his appreciation for Emile den Tex, particularly for the efforts he took to close the oceans separating geological and geophysical worlds. His wisdom prevented large collisions.

OPENING AND CLOSING OF SMALL BASINS AND SUBDUCTION OF YOUNG LITHOSPHERE

One of the reasons of the observed complexity of Alpine orogeny (ZWART & DORNSIEPEN, 1978) is that many passive margins of small ocean basins have been created and subsequently destroyed.

Timing of opening and closing of Alpine basins.

Spreading in the Alpine realm started about late Middle Jurassic (165-160 Ma) (TRÜMPY, 1982). This is concurrent with the revised timing of the opening of the Central Atlantic Ocean (165 Ma) inferred from recent DSDP data (SHERIDAN & GRADSTEIN, 1981). The spreading process led to the creation of Alpine troughs and oceanic basins, and took place in a tectonic setting of transcurrent displacement of the African plate with respect to the European plate. Spreading in the Alpine region was preceded by a phase of thermo-mechanical thinning of the lithosphere, due to rifting and extension (TRÜMPY, 1982). Lithospheric thinning probably goes along with anatexis and ductile deformation of the lower crust (DEN TEX, 1982; VLAAR, 1982).

The amount of spreading and transcurrent motion is still a matter of debate (e.g. TRÜMPY, 1982; LAUBSCHER & BERNOULLI, 1982). The total sinistral displacement of Africa and Europe has been of the order of some 1000 km (PITMAN & TALWANI, 1972). This does not imply that the relative movement has been taken up completely in the Alpine realm. In any case, the creation of basins and troughs rules out transcurrent motion along a single straight transform fault segment; instead a more irregularly shaped geometry is required.

From middle Cretaceous (105-100 Ma) onward, transcurrent displacement and compression resulted in the closing of the basin complex, and that was virtually completed by mid Eocene time (TRÜMPY, 1982). This last author estimated total shortening in the Central Alps to be of the order of 250 km. The total transcurrent movement cannot have exceeded 1000 km and may be only a fraction of this amount. Accepting the Insubric line as the main suture between the Apulian and European plates, the question arises to which extent closing has been perfect. We reject large scale overlap of the European and Apulian continental platforms on mechanical grounds, and consequently, large scale subduction of continental lithosphere. This, however, does not prevent small scale overlap in a concentrated compressive regime in the latest stages of orogeny to cause complexities like the Zermatt-Saas Fee and Sesia Lanzo zones, and the Ivrea body. Data on the area of autochthonous oceanic basement can provide a clue to which extent complete closing has occurred. In this context, we consider the basements of the Southern Alps (as exposed in the Ivrea body) as particularly interesting. The ultrabasic character of the Ivrea body points to an oceanic upper mantle structure, which has been deprived of the overlying crust. We suggest that the oceanic crust has been emplaced as an ophiolite thrust sheet in the early stages of nappe transport, forming one of the upper floors of the nappe 'Stockwerk'.

Subduction of young oceanic lithosphere

On the base of the evidence mentioned above we assign a maximum age of 60 Ma to the oceanic lithosphere that was formed during spreading in Alpine basins, when closing started. Consequently, the age of the lithosphere when being subducted during closing ranged in age from 0 to 60 Ma. Therefore, 'classical' Benioff subduction has to be ruled out (VLAAR & WORTEL, 1976): a possible reason for the absence of island arc volcanism in the Alps. At the onset of basin closure, subduction has to be initiated. The Alpine basins, being characterized by young oceanic lithosphere, transcurrent faulting, extensive sediment loading, and a compressive regime, then prove to be ideally suited for the transformation from passive to active continental margins (CLOETINGH, 1982; CLOETINGH ET AL., 1983, in press.). We do not speculate on the location of initiation of subduction in the Alpine basins nor on the direction of subduction, if not directly relevant to geological observations. SMITH (1981) has demonstrated convincingly for the western Cordilleran North American thrust belt that the direction of subduction does not uniquely determine the direction of coeval nappe emplacement, which is contrary to assumptions usually made for nappe emplacements in the Alps (e.g. LAUBSCHER & BERNOULLI, 1982). We, therefore, reject the common notion that nappe emplacement results from ongoing subduction related compression and decollement in trench deposits.

ENGLAND & WORTEL (1980) and WORTEL & CLOETINGH (1983) have shown that for the case of subduction of young oceanic lithosphere a compressive regime at the active margin is induced. Hence, we expect melanges, involving the occurrence of ophiolitoïds (TRÜMPY, 1982) due to off scraping of ocean floor or intrusion of magma from a diffuse spreading centre into overlying sediments (KELTS, 1981), to be a characteristic feature of Alpine orogeny. Furthermore, basin closure is associated with high P/low T metamorphism of the sediments on top of the young lithosphere. This is particularly the case for the Bündnerschiefer deformation.

LITHOSPHERIC DOUBLING AND SHIFTING AS A MECHANISM FOR ALPINE GRAVITY TECTONICS

Lithospheric doubling

Oceanic ridge segments which were formed during opening of the Alpine basins are bound to be subducted, or rather to be overridden by the cooler continental platform lithosphere when basin closure takes place. This process has been termed lithospheric doubling (VLAAR, 1982; 1983a): relatively cool lithosphere is superimposed on a young, buoyant and hot oceanic ridge with adjacent flanks and underlying upper mantle. The doubled system initially is characterized by a thermal anomaly below the upper cool lithospheric plate and consequently by a density inversion at depth. The resulting gravitationally instable configuration induces buoyant uprising of hot mantle material. Lithospheric doubling as such may account for uplift of the earth's surface of the order of at least some 500 to 1500 m (VLAAR, 1983b). An uplift of this order of magnitude might, when associated with a thermo-mechanical thinning of the upper plate, suffice to allow effective uprise of magma through the upper lithosphere (CLOETINGH & NIEUWLAND, in press). Moreover, in the Alpine setting, uprise of magma is facilitated by the presence of transcurrent faults transecting the entire upper plate. Although relatively little surface manifestations of magmatism occur, there is abundant, strong, seismic evidence (e.g. MUELLER, 1982) for the presence of thermal anomalies in the crust and upper lithosphere in the Alps. Upwelling of mantle material associated with lithospheric doubling generates both the upbulging necessary for gravity sliding or gravity spreading, as well as the elevated temperatures required for metamorphosis.

Lithospheric shifting

Thrust sheet emplacement due to gravity spreading of the sedimentary cover off an upbulged metamorphic source area has been proposed by SMITH (1981) for the North American Cordillera. Eastward stacking of the thrust sheets, which are made up of a well developed passive margin sequence, thickening westwards to values of 10 km, has been attributed by the same author to an eastward migration of the source area. SMITH (1981) ascribed the moving source area to a continuous decrease of the angle of subduction of the slab being subducted at the Pacific-North American margin.

We propose an alternative mechanism in which the migration of the source area is due to the westward shift of the North American continent over young oceanic lithosphere and numerous spreading ridge segments, hence, to lithospheric doubling and subsequent shifting. Magmatic and metamorphic activity is particularly manifest at the location of former transform fault boundaries causing aligned metamorphic core complexes. The role of transform faults, associated with spreading centres, in orogeny has been previously advocated by WYNNE-EDWARDS (1976). He did not, however, provide a mechanism explaining the presence of spreading segments under continental lithosphere. Furthermore, migrating uplift induced by lithospheric shifting (VLAAR, 1983b) provides a rationale for the widely observed thrust sheet complexes emplaced and stacked in a so-called piggyback fashion (ELLIOTT, 1976). We propose that lithospheric shifting upon closing of Alpine basins took place due to continued spreading in the North Atlantic and, consequently, south-eastward shifting of the European continent over the upper mantle source of a former oceanic spreading centre or over the overridden ridge itself. However, it should be noted that paleomagnetic evidence related to the shifting of the European continent appears to be lacking for the period considered.

Scenario for emplacement of the most southerly derived Alpine nappes

Basin closure moved from the internal to the external parts of the orogen (FRISCH, 1981) and stacking of thrust sheets in that direction progressed with time. Nappes of the Austro-Alpine have been emplaced in some cases on top of an ocean floor, which has been subsequently emplaced as an ophiolite nappe on a passive continental margin. For the initial stages of upbulging and gravity tectonics leading to the emplacement of the nappes of the most southerly derived Alpine units, we propose the following scenario:

The Austro-Alpine nappes are derived from south of the main Alpine suture and, hence, from the 'wrong' side of a possibly southward dipping subduction zone. If southward dipping subduction took place, it must have involved young and gravitationally stable oceanic lithosphere and probably ridge segments. We, therefore, prefer obduction of the Apulian (micro) plate over the young oceanic lithosphere. Lithospheric doubling and, hence, creation of an upbulging source area caused gravitational emplacement of the Austro-Alpine cover over the more northerly oceanic crust and/or platform sediments.

The foregoing scenario explains the tectonic superposition of the Austro-Alpine, for instance the lower Austro-Alpine Err nappe in the Central Alps on top of upper Penninic ophiolite sheets of the Platta nappe. The latter, then, should have constituted oceanic crust stripped of oceanic upper mantle to be found south of the Insubric line.

Ophiolite thrust sheets

In the present paper, we confine ourselves to ophiolite thrust sheets emplaced along Alpine passive margins. Other ophiolite complexes emplaced on top of passive margin sediments are the Mesozoic Semail ophiolite of Oman (BOUDIER & MICHARD, 1981) and the Palaeozoic Newfoundland ophiolite

(DEWEY, 1976) both of which are particularly well preserved. Here, the complete sequence consists of a shelf platform followed by thrusted layers of slope, rise and deep-water sediments with the ophiolite forming the top thrust sheet. Although less clearly developed elsewhere, such a layering seems to be a universal characteristic of ophiolites emplaced along passive margins (SMITH & WOODCOCK, 1976). The Alpine situation, where Austro-Alpine nappes are emplaced on top of an ophiolite complex, is a complicating exception to the rule.

The following general observations are consistent with initiation of subduction and emplacement of ophiolites along passive margins of small and short-lived oceanic basins, and apply to the Alpine setting as well.

1. The short time interval documented between ophiolite formation at the spreading ridge and ophiolite emplacement along the margin (NICOLAS & LE PICHON, 1980). In this connection we note that BOUDIER & MICHARD (1981) showed that the Semail ophiolite of Oman was emplaced along the passive margin, within 20 Ma after creation at the spreading ridge.

2. The general absence of island arc volcanism at margins prior to the emplacement of ophiolites (BOUDIER & MICHARD, 1981; SMITH & WOODCOCK, 1976). When ophiolite emplacement would have taken place at the last stage of closing of a major oceanic basin, such island arc activity associated with ongoing subduction of old oceanic lithosphere would be expected.

3. Crustal sections of ophiolites are usually thinner than thicknesses assigned to standard oceanic crust (GASS & SMEWING, 1981), but fit with thinner crustal thicknesses of young oceanic (near ridge) crust.

4. Total thicknesses of ophiolite sheets are typically less than 10 km (COLEMAN, 1971). It is reasonable to suppose that the thickness of the ophiolite is related to the depth of the decollement with the underlying mantle. Thrusting of young lithosphere has been proposed by NICOLAS & LE PICHON (1980) to explain decoupling of the ophiolite sheet at depths shallower than 10 km. CLOETINGH (1982) has shown that a thickness of the order of 10 km of the mechanically strong part of the lithosphere is a characteristic feature of oceanic lithosphere of ages of 10-20 Ma.

5. Gravitational tectonics as a mechanism for ophiolite emplacement has been advocated earlier by several workers (e.g. DEWEY, 1976). Emplacement of ophiolites on passive margins is facilitated when the ophiolite sheet is derived from young, gravitationally stable and buoyant (VLAAR & WORTEL, 1976) oceanic lithosphere.

FURTHER IMPLICATIONS FOR ALPINE OROGENY AND FORELAND TECTONICS

Departing from the foregoing considerations, we propose the following sequence of tectonic events which appears to comply with Alpine geological and geophysical data.

Penninic nappes

While affecting the emplacement of the S.Penninic nappes, thermally anomalous mantle (apparently) migrated northwards, when lithospheric shifting proceeded. Its interaction with local transcurrent faults facilitated the rising of magma to crustal levels. In addition, the thermal anomaly may have stagnated spatially, because of the closing of more northerly situated (N. Penninic) basins. This resulted in magmatism (e.g. the Eocene-Oligocene emplacement of the Bergell granodiorite) and large scale high T metamorphosis of the emplaced nappe complex (Lepontine event) and anatexis of the basement. The basement thereby acquired a ductile rheology and was able to flow, forming nappe- and mushroom-like structures. The relief created by updoming, also on deeper levels, should determine the direction of ductile flow. Usually, the depth of burial of the basement under the pile of nappes is held to be responsible for high grade metamorphism. However, OXBURGH & TURCOTTE (1974) have shown that this mechanism cannot produce the necessary temperatures within tens of millions of years. Therefore, enhanced heatflow from lower crustal levels is required. Such an enhanced heatflow is a natural consequence of the mechanisms presented here.

We also note that the processes described must account for considerable inversion of relief. Once an upbulging thermal dome has been deprived of its cover, rapid cooling and subsidence sets in. Migration of the thermal anomaly causes uplift of the thrust sheet stack after emplacement.

Western Alps

Though a decline of intensity of the thermally anomalous upper mantle due to conductive and advective cooling is to be expected, it has been shown that the thermal relaxation time involved is of the order of least tens of Ma (VLAAR, 1983b). Therefore, further migration of the (weakening) thermal anomaly may have produced repetition of its activity in space and time. This is to be expected when it moved under more northerly situated weakness zones and fault systems in the shifting lithosphere. A prime structure of this sort is the Rhine graben, which extension has been delineated by seismic experiments (RYBACH ET AL., 1980) to well below the Alpine chain. It may even be present underneath the Western Alps, where Moho depths are extremely large. This may account for the considerable crustal shortening of the Western Alps. Reactivation of this graben system by the migrating thermal anomaly could have resulted in thermo-mechanical weakening of the lithosphere, penetration of magmas to high levels and associated updoming of the crust. The presence of a former thermal event is indicated by low crustal seismic velocities below the Western Alps (MILLER ET AL., 1982). Crustal doming forms an explanation for the latest Miocene and Early Pliocene gravitational emplacement of the Jura nappes. At these stages, thermo-mechanical weakening of the lower crust may have caused 'retrocharriage' of deeper lying nappes in a south-easterly direction. Back-thrusting with apparently vergence to the south forms a prominent feature in many parts of the Penninic nappes in the Valais.

Northern forelands

Apart from epeirogenetic uplift of the Alps proper, further post-Alpine effects to the North of the Alps are a logical consequence: spreading in the North Atlantic is proposed to have caused shifting of part of Northern Europe over thermally anomalous mantle produced by Alpine basin formation with an associated uplift of a maximal order of 1-2 km (VLAAR, 1983b). For the German 'Mittelgebirge' we require only a fraction of this amount. It has been documented (ILLIES, 1978) that a northward progressing reactivation of the Rhine graben took place during the Pliocene-Quaternary. The upper Rhine graben and the adjacent Black Forest-Vosges uplift are characterized by updoming of the Moho and an inferred hot upper mantle (WERNER ET AL., 1982). Northward migration may also have effected the Eifel volcanism and the weak activity of the Ruhr graben well into The Netherlands.

Although reactivation of the Rhine graben has been manifest, it appears that perturbation of the lithosphere has been mainly effected through older Hercynian fault systems possibly giving rise to the uplift of the Ardennes and the Rhenish massif. In the same fashion we ascribe Pleistocene-Quaternary uplift and volcanism of Schwaben, and the Bohemian and Central massifs to thermal perturbation of the upper mantle, which was related to spreading in the Alpine realm, in the Pannonian basin and in the Mediterranean.

At present the detailed history of the closing of the Alpine basins is not yet known. The closing sequence of these basins should determine the succession of northward migrating events North of the Alps.

CONCLUSIONS

The scenario developed here explains many features of (Alpine) orogeny and associated foreland uplift and tectonics. This scheme contains the following elements that have hitherto not been taken into account and that may prove to be crucial for understanding many phenomena of intracontinental tectonics:

1. The role played by age-dependent subduction and a related compressive regime upon the closing of small and young oceanic basins.
2. The induction of a thermally anomalous state of the upper mantle by ocean spreading itself and/or of lithospheric doubling.
3. The apparent migration of a thermally perturbed mantle caused by lithospheric shifting. In particular, when the shifting lithosphere is transected by older fault systems and weakness zones, this may result in upward migration of magma, anatexis and ductile flow of the lower crust, metamorphosis and doming. This doming induces gravity tectonics.

We are aware of the necessity to confront our hypothesis with further geological and geophysical evidence, and also to cast the employed tectonophysical models in a more quantitative framework. RUTTEN (1968) has summarized ample evidence in favour of gravity tectonics as the prime agent for nappe emplacement in the Alps. The view that Alpine tectonics is primarily due to collision and compression, however, is widespread.

We notice that Alpine orogeny shows some special features, which in general are not involved in the emplacement of fold belts as such, and which are purely circumstantial and complicating:
1. The presence of the southern extension of the Rhine graben underneath the Alpine chain. This structure has probably acted as an effective feeder of magma to crustal levels, thus, causing an extensional regime in, and uplift of the source area of the Jura mountains (ZIEGLER, 1982); and more to the south gave rise to 'Rückfaltung' of the mobilized basement.
2. The compressive state, first causing closure of the Alpine basins, has persisted in the global tectonic framework of the convergence and right lateral movement of Africa and Europe. This has led, in the final stages of Alpine orogeny to concentration of pressure and some overlap of existing margins in the Central and Western Alps, leading to apparent subduction of continental lithosphere (so-called A-subduction). Although, because of the thermally weakened lithosphere north of the Alpine suture, some compression should not be ruled out, we regard these particular phenomena of Alpine orogeny ('Verschluckungszone') to be due to circumstances, not specific for the formation of thrust belts in general.

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