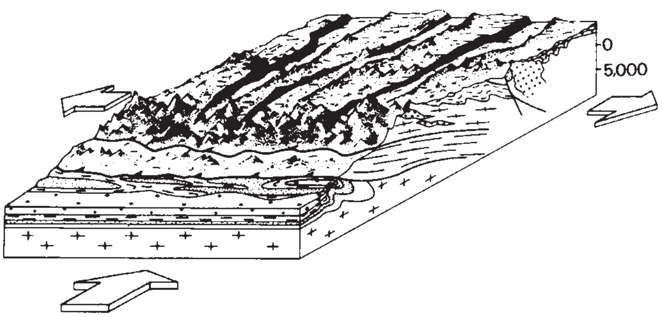

Fig. 5 Idealized block diagram shows how, whereas folding and shortening of the crust still occurs in the Siwaliks and lower Himalayas in response to the northward penetration of India into Asia, east–west extension now predominates on the high Tibetan plateau.

Conclusions

Although north–south shortening of the crust is evidenced by upright folds and cleavage in early to middle Cretaceous sediments and much more gentle folding in late Cretaceous and early Tertiary sediments[6,13,14], shortening has apparently not been a dominant process in the late Cenozoic tectonics of southern Tibet. During the upper Quaternary at least, but perhaps for a longer period of time, east–west extension must have prevailed on the Tibetan plateau. North–south normal faulting has been especially active in the past several thousand years. As in other areas such as the Aegean in the Mediterranean, or the Basin and Range in North America, such faulting appears to be distributed over a wide area.

The faults are perpendicular not only to the Himalayan belt in which they stop rather abruptly, but to most of the more ancient Mesozoic and Tertiary fold trends and roughly east–west structural and palaeogeographical zones within the plateau. In particular, the fault systems cut through major sutures such as the Yarlung Zangbo. Thus, although deviation by more ancient structural trends is possible (Fig. 1), a large proportion of the north–south normal faults are probably not reactivated older ones as has often been suggested[15]. Hence, perhaps more than in any other region, extension in Tibet seems to reflect a particular state of stress in the crust and upper mantle, where gravity can be the main driving force. Microtectonic observations made during the Chinese–French expedition support this inference.

Although further speculations on the cause of the east–west extension must await a better knowledge of the upper mantle and crustal structure of Tibet, the approximately double thickness of the continental crust as well as the softness of the hot lower crust[16] probably favour east–west flow in response to India's northward push[5,17].

Now that widespread normal faulting on the Tibetan plateau can be considered more firmly established, important questions remain for future field work: when did incipient extension take over folding and crustal thickening? Does the time when this change occurred compare with the time when Tibet acquired its abnormally high elevation? At what rates has east–west stretching of the crust taken place since then?

New data on these questions will surely place constraints on how large and high plateaus form and evolve during continental collision.

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The Xigaze ophiolite (Tibet): a peculiar oceanic lithosphere

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The Xigaze ophiolite which outcrops along the Yarlung Zangbo river, southern Tibet, locally displays a complete ophiolitic sequence from marine sedimentary cover over basaltic volcanics to the north, to fresh Cr diopside-rich harzburgites to the south. In contrast with other ophiolites, the mafic part of the sequence is particularly thin. It is almost devoid of cumulate gabbros consisting of a diabase sill complex covered by lava-flows or pillow-lavas. The ultramafic unit is poor in residual harzburgites and dunites and consists dominantly of fresh Cr diopside-rich harzburgites. The origin of this peculiar ophiolite (of oceanic crust) is discussed.

OPHIOLITE complexes in various parts of the world display remarkably comparable sections with, from top to bottom, basaltic lavas, dolerite dykes, isotropic gabbros, cumulate gabbros and ultramafic rocks, resting on tectonic dunites and harzburgites. The mafic part of these complexes usually represents a thickness of between 3 and 6 km (refs 1,2). It is this remarkable homogeneity, at least in their gross features, which led to the concept of ophiolites and to its informal definition[3]. In contrast to this homogeneity, various oceanic environments have been considered as potential sites for the origin of ophiolites: oceanic ridges with various spreading rates[4–10], back-arc basins[11,12], island arcs[13,14] and even transform faults[15]. The Xigaze ophiolite outcrops in Tibet along the Indus–Zangbo suture zone, one of many sutures which separate the Indian continent from the northern plate(s). Only limited data are available about these ophiolites[8,10] although they have been discussed in a recent report[16] that draws attention to the presence of limited amounts of cumulate gabbros and suggests that they may well correspond

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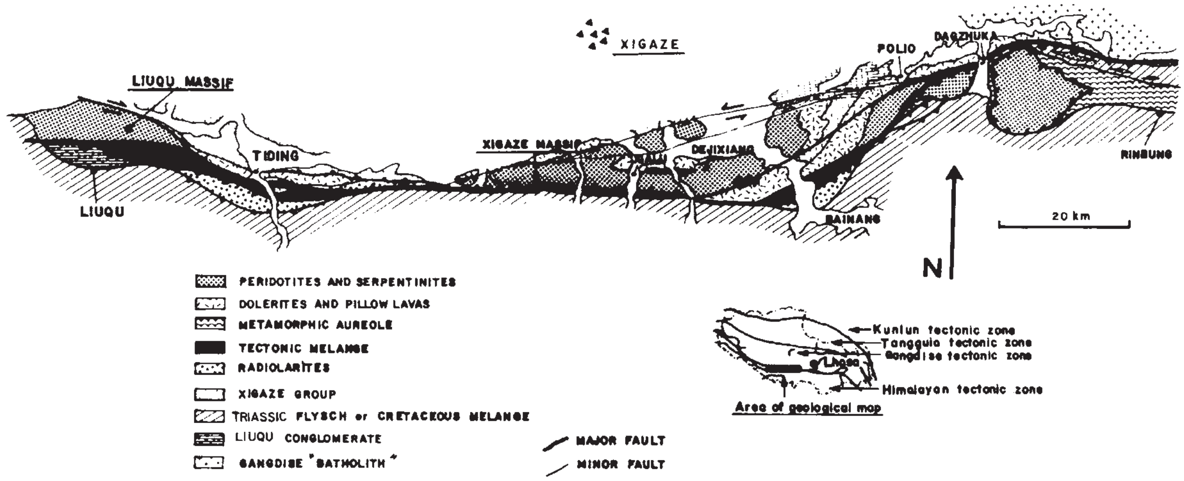

Fig. 1 Geological map of the Yarlung Zangbo ophiolite belt around Xigaze.

to a slow-spreading ridge on the evidence of a "thin, perhaps discontinuous plutonic sequence".

Considering that, as far as we know, ophiolites without cumulate gabbros have been identified only in highly dismembered massifs, the detailed structural study of the Xigaze ophiolite was of particular interest. It should contribute to the discussion on the relation between the existence of magma chambers in the oceanic crust beneath spreading centres and the problems of rate of partial melting in the mantle and rate of oceanic expansion.

The Xigaze ophiolite

The Indus–Zangbo suture in Tibet is commonly marked by a discontinuous line of serpentinites or by minor ophiolite bodies. The Xigaze ophiolite belt is >170 km long in the east–west direction of the suture and has a maximum width of 20 km (Fig. 1). It contains three areas where large masses of ultramafic and mafic rocks have been preserved from the intense deformations observed elsewhere along the suture zone: the Dagzhuka, the Xigaze and the Liuqu massifs. In the Dagzhuka and Xigaze massifs, a sequence from sedimentary cover over basaltic volcanics to the north to fresh harzburgites rich in Cr diopside to the south has been identified. Together with more partial sections such as those of Dejixiang, Polio and Tiding they enable a schematic cross-section to be constructed for the Xigaze ophiolite (Fig. 2).

Due to collision along the Indus–Zangbo suture zone, the ophiolites in the Xigaze area have been tilted into a 060°, 60°NW attitude with only local variations. As a result, the top of the sequence and its sedimentary cover are located to the north of the section. Generally, the main lithological contacts in the ophiolite, oriented at 060°, 60°NW, are few tectonized. They contrast with the east–west contacts, the main one being the southern limit of the ophiolite, which cut the former and are systematically tectonic.

From north to south (Fig. 2) one first meets the Gangdise 'batholith' which is commonly ascribed to an island arc or a continental active margin environment[13,18]. Its location relative to the suture, its east–west orientation and its lithologies point to the presence of an underlying, northward subduction zone. The northern part of the Xigaze group is considered as an essentially detrital formation accumulated on the southern margin of the granodiorite (Gangdise) massif. Its contact with the ophiolite often is a stratigraphic one with a few metres of cherts over the basaltic volcanics, covered by marine pelagic sediments reworking in various proportions the underlying volcanics[19].

Below the cherts either pillow-lavas or lava-flows are observed (Fig. 3). They are parallel to the chert orientation with local departures in the pillow-lavas. The polarity in the pillow-lavas is always with the top northward. Their diameter in section is smaller than 60–80 cm and they are often extended in tubes with no particular directions. They are either largely variolitic, with 1-cm varioles or massive with only a finer grain rim. Their matrix is not abundant and exclusively constituted by volcanic debris and glass. Beneath a few hundred metres of volcanics, the first diabase dykes and sills appear. They typically present chilled margins and have been observed cutting through the pillows. They progressively become more abundant until they constitute a sill complex with sills intrusive into sills. The sill rather than dyke nature is deduced from their general parallelism with the overlying volcanic lava-flows and sediments. A few dykes, normal to the sills, are often present (Fig. 3); these can be very abundant in some massifs such as Dagzhuka. The thickness of individual sills is in the metre range. When they reach a few metres, microgabbro textures can be obtained in their core. New sills intrusive in such rocks can create the illusion that they are intrusive in a fine-grained gabbroic formation. True plutonic rocks are uncommon between diabase sills with the exception of a few isotropic gabbros and trondjhemite screens.

In the Dagzhuka and Tiding massifs (Fig. 1), small bodies of cumulate gabbros and ultramafic rocks are locally present at the base of this sill complex. In these massifs, the thickness of the cumulate olivine gabbros is <170 m and <120 m respectively. In the Dagzhuka massif, the walls of the chambers are made of troctolites and dunites which can be interpreted as the first cumulates or, alternatively, as residual wells impregnated by feldspar coming from the chamber. The shape of the magma chambers is very irregular and, in Dagzhuka, the total thickness mentioned above could be achieved by addition of smaller chambers. In Tiding, there is a remarkably thick sequence of isotropic gabbros which may represent the upper part of a comparatively large magma chamber.

The thickness of this crustal unit does not exceed 3 km. It lies over a serpentinized harzburgite and dunite formation penetrated by numerous diabase sills. Those sills which can constitute 50% in volume of this new formation are often particularly thick, up to 7 m. They have been observed to branch to perpendicular dykes which probably represent their feeders. A few rodingitized gabbro dykes also intrude the ultramafic rocks but they are cut by the diabase ones. In contrast with the gabbros, the diabase dykes seem to be usually fresh or rodingitized only along their margins. As rodingitization probably accompanies the serpentinization of the peridotite[20], it can be concluded that the gabbro dykes were emplaced before the serpentinization and the diabase ones, after it or late during the process. The peridotite structure is not altered by the serpentinization except locally where low-temperature deformations have disrupted and boundinaged the dykes and developed a slickenside cleavage in the serpentinites. As a consequence the coarse porphyroclastic texture of the peridotite, typical of high-temperature flow[22] is still visible and its orientation can be mapped. The foliation is represented with its field orientation in Fig. 2 and with its restored orientation in Fig. 3. The thickness of

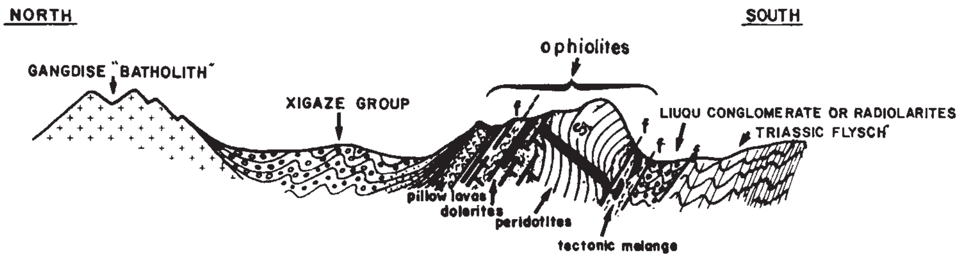

Fig. 2 Schematic north–south cross-section through the Yarlung Zangbo suture near Xigaze. S_1, foliation.

this harzburgite and dunite formation containing the sills is 500 m on average with important local variations. Downwards it grades into a 500-m unit formed of serpentinized foliated harzburgites and dunites with a decreasing amount of gabbro and diabase dykes. The degree of serpentinization rapidly decreases in these peridotites. After 1–2 km of relatively fresh harzburgites and dunites, fresh harzburgites with a crude layering resulting from the alternation of Cr diopside-rich and Cr diopside-poor facies, visible at various scales are encountered. No banding is observed in these rocks except for a few pyroxenites. The rocks are well foliated with discordant shear zones represented by a few metres of mylonitic peridotites in the Xigaze and Liuqu massifs (Figs 2, 3). Outside these bands, fine to coarse-grained porphyroclastic structures related to high-temperature plastic flow are observed. At the massif scale, the tectonic structures display a relatively irregular pattern though remaining consistent from one massif to another[17].

The southern east–west contact of the Xigaze ophiolite with the sedimentary formations is tectonic. Over 500–800 m, the ultramafic rocks are transformed into an ophiolitic mélange with blocks of rodingitized gabbros and diabases floating in a schistose serpentinite. On the other side of this major tectonic contact, either radiolarites or a coarse red conglomerate separate the ophiolites from the Triassic flysch series. They are also strongly deformed and schistozed at the contact but, like the serpentinites, are devoid of any metamorphism.

Amphibolites, garnet amphibolites and quartzites have been observed in several localities (Liuqu, Bainang and Dagzhuka) as inclusions in the serpentinite mélange. In the Dagzhuka massif, mylonitic peridotites are developed over several dozen metres above the basal contact which contains blocks of amphibolites in a serpentinite matrix. Beneath, a metamorphic formation consisting of quartzites, phyllites and locally ophicalcites, outcrops over 300 m. This might represent the basal part of the metamorphic aureole well known in many ophiolites[22,23].

Discussion

Considering the general tectonic situation, special attention must be devoted to the question of continuity within the ophiolites mainly at the critical level between the mafic and ultramafic formations. This continuity is thought to be locally preserved for the following reasons.

First, the sills and the dykes are remarkably continuous, keeping the same attitude from the volcanics down to the upper peridotites; and second, the same general sequence is systematically observed along the area studied (Fig. 1). In particular, the possibility of a squeezing out of the gabbros is remote, considering that no large masses of gabbros have been found. On the other hand, isolated pockets of gabbros are now well identified within the mafic part of the sequence. We thus think that the gabbros have not been faulted out and that a continuous section was observed in the Xigaze area.

The specific characters of the Xigaze ophiolite can be summarized as follows:

(1) In contrast with other non-dismembered ophiolites, the mafic part of the sequence is nearly devoid of plutonic rocks except for the small cumulate gabbro bodies found in the Dagzhuka and Tiding massifs. The mafic formation is entirely comprised of basaltic volcanics overlying diabases and dolerites with isotropic gabbro screens and, more rarely, trondjhemite screens.

(2) The diabase unit is a sill complex and not a dyke complex, as expected, with sills intrusive one into the other and only a few branching dykes at right angles to the sills. This has not yet been described in ophiolites except in the Point Sal ophiolite[24].

(3) This mafic part of the sequence is remarkably thin (compared with that measured in non-dismembered ophiolites) with local variations in thickness, but does not exceed 3 km.

(4) The upper harzburgites and dunites are invaded by thick diabase sills over a thickness of ~1 km. To our knowledge, this is also unique as diabase dykes are very scarce in the few ophiolite massifs where they have been described cross-cutting the harzburgites[25].

(5) Cr diopside-rich harzburgites are abundant in the ultramafic unit and appear only at 2 km beneath the mafic unit and at 5 km beneath the sedimentary cover of the ophiolite sequence. This is unique as the ultramafic unit in ophiolites is usually composed of depleted harzburgites with Cr_2 diopside-rich harzburgites appearing only in the basal section in a few massifs[27].

(6) Local thin shear zones inside the ultramafics with low-temperature plastic flow structures have not been described in ophiolites. Those observed are generally located at the base of the ultramafics. They are thicker and clearly related to late thrusting of the lithosphere[28].

Depending on the spreading rate, the structural, petrological and geochemical character of oceanic spreading centres are expected to vary. The difference seems to be essentially controlled by the heat budget[29,30]. Slow-spreading ridges will have a lower rate of magma generation and therefore of heat production for a comparable thermal dissipation rate. As a

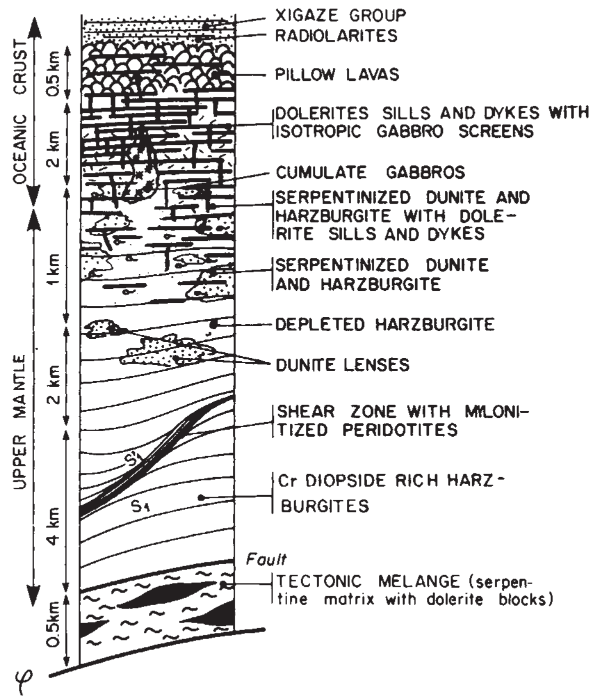

Fig. 3 Schematic cross-section of the ophiolite sequence. Solid lines represent the foliation S_1. The smaller the spacing, the higher the strain. The various attitudes have been restored after a rotation to horizontal of the radiolarites and basalt flows.

result, magma chambers where the gabbro cumulate sequence crystallizes are not expected for spreading rates of <1 cm yr^{-1} (refs 31, 32). Steeper isotherms in the mantle should tend to concentrate the magmatic and tectonic activity closer to the ridge than in fast-spreading ridges. However, as mentioned elsewhere[33], one of the bases for these thermal models is that the upwelling rate of the asthenosphere is proportional to the rate of spreading. The fact that spreading is a discontinuous phenomenon is likely to change these conclusions.

If these conclusions are applied to the Xigaze ophiolite, our evidence indicates a crust formed at a spreading centre with a particularly slow spreading rate, <1 cm yr^{-1} if one accepts this limit for the transition from continuous to discontinuous magma chambers. This interpretation differs significantly from that of Wu Haoruo and Deng Wanning[14] who think—based on major element chemistry—that the Xigaze ophiolite has been formed in a subduction zone environment. Further detailed geochemical studies are necessary, however, as most of the studied mafic rocks are altered.

Although the mafic crust in our case is only ≤3 km on average, the geophysical Moho would be deeper, considering that the 1–2 km of serpentinized peridotites with up to 50% in volume of diabase sills display crustal seismic velocities. Our evidence that serpentinization occurred before the diabase emplacement shows that these peridotites were serpentinized at the ridge itself and therefore that they belong geophysically to the crust. The 'geophysical crust' would therefore have a thickness comparable with that determined by a V_p transition from 6.8 km s^{-1} to 8.1 km s^{-1} for slow ridges like the Atlantic one[34].

Finally, if the interpretation that the Xigaze ophiolite originated at a slow ridge is correct, the study of its structure, petrology and geochemistry bears directly on the structure and nature of slow ridges. In this respect, the occurrence of a sill complex as the main component of the crust, which also extends in the uppermost mantle, is interesting.

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Antibodies to left-handed Z-DNA bind to interband regions of *Drosophila* polytene chromosomes

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Antibodies which are specific to the Z-DNA conformation have been purified and characterized on the basis of their binding to three different DNA polymers which can form this left-handed helix. These antibodies bind specifically to polytene chromosomes of Drosophila melanogaster *as visualized by fluorescent staining. The staining is found in the interband regions and its intensity varies among different interbands in a reproducible manner. This is the first identification of the Z-DNA conformation in material of biological origin.*

LEFT-HANDED double-stranded DNA was first discovered by an atomic resolution X-ray crystallographic analysis of the hexanucleoside pentaphosphate CpGpCpGpCpG (ref. 1). In this conformation the DNA formed a double helix with Watson–Crick base pairs and antiparallel sugar–phosphate chains; the sugar–phosphate backbone followed a zig-zag course and for this reason was named Z-DNA. In Z-DNA the guanine bases have rotated about the glycosydic bond and have assumed a *syn* conformation, in contrast to the *anti* conformation in B-DNA. The early observation by Pohl and Jovin[2] of salt-induced inversion of the circular dichroism spectrum of poly(dG-dC) DNA in 4 M NaCl solution can now be understood as the conformational transition of the right-handed B-DNA to the left-handed Z-DNA[3,4]. Z-DNA has been seen in several crystal structure and fibre analyses[5–8] and generally, DNA with alternating purine–pyrimidine sequences may be expected to have Z-forming potential.

We have recently demonstrated that left-handed Z-DNA is a strong immunogen; in both rabbits and mice antibodies can be raised which are specific for the left-handed Z conformation and will not react with right-handed B-DNA[9]. Because of their specificity, antibodies can be used to determine the distribution

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