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Precise radiolarian age constraints on the timing of ophiolite generation and sedimentation in the Dazhuqu terrane, Yarlung–Tsangpo suture zone, Tibet

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Abstract: Well-preserved, abundant radiolarians provide high-precision biostratigraphic age constraints on the timing of the eruption of ophiolitic basalts exposed along the Yarlung–Tsangpo suture zone in southern Tibet. Dazhuqu terrane ophiolites were generated in an intra-oceanic supra-subduction zone setting within a relatively short (<10 Ma) interval from late Barremian to late Aptian. Accumulation of sediments upon the newly generated ophiolite initially occurred in a series of discrete rift-controlled sub-basins associated with various spreading centres. An increasing flux of arc-derived volcaniclastic sediment up-section indicates nearby volcanic arc activity. The Dazhuqu terrane developed in an intra-oceanic setting within Tethys where it was isolated from any continental influence.

Keywords: Radiolaria, Yarlung–Tsangpo suture, Tibet, ophiolites, biostratigraphy.

The Yarlung–Tsangpo suture zone in Tibet marks the tectonic boundary between Eurasia and India. The previously vast Tethys ocean finally closed along the suture during their Cenozoic collision. Most of this ocean was lost through subduction during convergence or was overridden during collision. All that remains now occurs within a suture zone of a few kilometres width. A belt of ophiolitic bodies is the most traceable feature along the Yarlung–Tsangpo suture zone, in south Tibet and beyond. Several ophiolitic massifs form a nearly continuous exposure that stretches east–west over a distance of *c.* 150 km near Xigaze, 250 km SW of Lhasa. These rocks are assigned to the Dazhuqu terrane and interpreted as having originated in an intra-oceanic supra-subduction zone setting (Aitchison *et al.* 2000, 2002a). This interpretation of the origin of the Dazhuqu ophiolite is supported by detailed mineralogical and geochemical studies in the Xigaze area (Hébert *et al.* 2000; 2001). The presence of these rocks together with other intra-oceanic terranes along the suture led to the suggestion of Aitchison *et al.* (2000) that a south-facing intra-oceanic subduction system once lay within the Tethys.

Knowledge of the timing of generation of the Dazhuqu ophiolite is a significant issue for understanding regional geology and has implications for development of models for Tethys evolution. Marine sedimentary cover on mafic volcanic rocks was previously dated as late Albian to possibly early Cenomanian (Marcoux *et al.* 1982) or early Cenomanian (Wu 1986) on the basis of radiolarians reported from the Xigaze district. These ages appeared to be some 20 Ma younger than a radiometric age of 120 ± 10 Ma inferred from U–Pb whole-rock analyses of gabbros, dolerites and basaltic lavas reported from the same area (Göpel *et al.* 1984). Until now, no further biostratigraphic study of the Dazhuqu terrane has been published. Meanwhile, Cretaceous radiolarian biostratigraphy for the Tethyan regions has developed significantly (Jud 1994; O'Dogherty 1994; Baumgartner *et al.* 1995). This opens the possibility for obtaining more accurate biostratigraphic information that will permit better recognition of any sequence of events related to development of the ophiolite. In the course of our study of the Dazhuqu terrane, we obtained new data on the lithostratigraphy and radiolarian biostratigraphy of the sedimentary succession overlying the ophiolite. These results constrain the timing of ophiolite formation and permit a better understanding of the development of sedimentary basins on this newly generated supra-subduction zone crust.

Regional tectonic framework

Six tectonostratigraphic units (terranes) that developed before India–Eurasia collision are recognized (Aitchison *et al.* 2000) within and bounding the Yarlung–Tsangpo suture zone (Fig. 1). The northern side of the suture is delineated by the Lhasa terrane, a microcontinental block that had detached from the northern periphery of Gondwana and docked with Asia by the Late Jurassic (Allègre *et al.* 1984; Yin & Harrison 2000).

A 5000–8000 m succession of volcaniclastic turbidites (Xigaze terrane) lies to the south of the Lhasa terrane. The Xigaze terrane is thrust northwards over upper Oligocene–lower Miocene Gangrinboche facies conglomerates (Aitchison *et al.* 2002b). At its southern boundary the terrane lies in the footwall of another north-directed thrust with Dazhuqu terrane ophiolitic rocks or Paleogene Liuqu Conglomerate (Davis *et al.* 2002) in the hanging wall. Rare fossils indicate that the turbidites have a late Albian to Coniacian stratigraphic range (Wiedmann & Dürr 1995; Wan *et al.* 1998). As the oldest known fossils are not from the base of the section it is possible that sedimentation may have commenced before the late Albian. The top of the Xigaze turbidite sequence is truncated by erosion. Xigaze terrane rocks are interpreted as a forearc succession that developed in association with north-directed subduction beneath the Lhasa terrane (Shackleton 1981; Burg & Chen 1984; Girardeau *et al.* 1984;

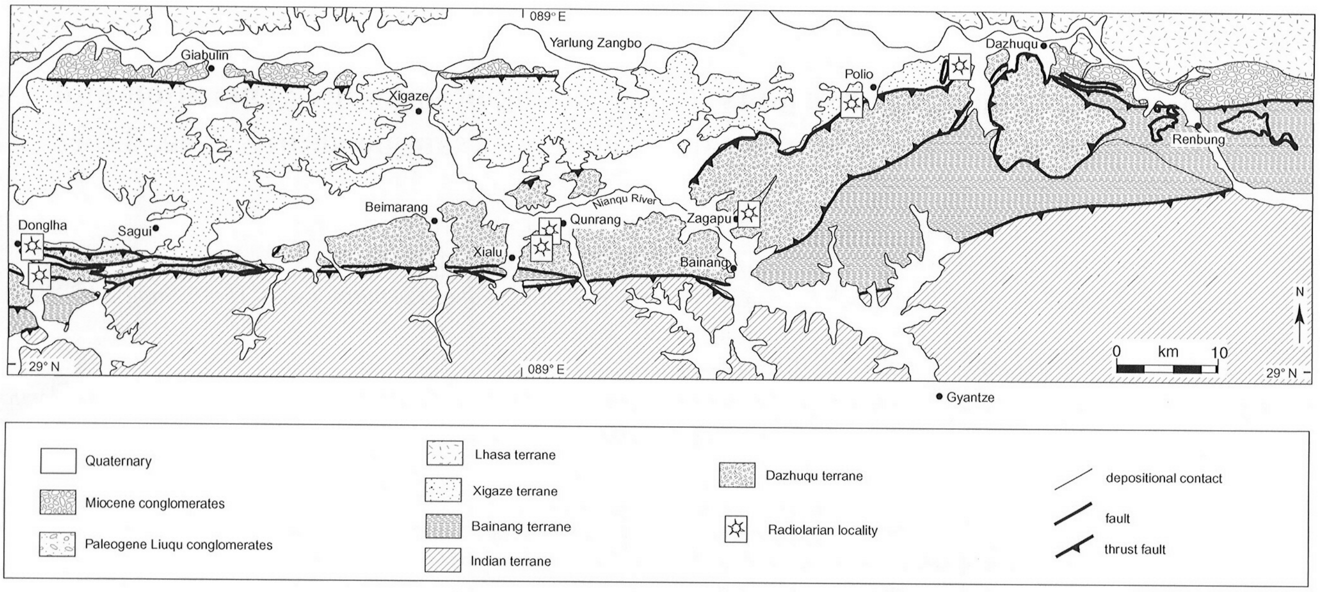


Fig. 1. Simplified geological map showing distribution of Dazhuqu terrane rocks near Xigaze (modified from Wang *et al.* 1987) and localities of the sections studied.

Einsele *et al.* 1994; Dürr 1996). Development of the terrane was related to evolution of the magmatic arc along the southern edge of the Lhasa terrane (Einsele *et al.* 1994; Dürr 1996). Although the Xigaze terrane is conventionally regarded as being floored by the Dazhuqu ophiolite (e.g. Burg & Chen 1984; Girardeau *et al.* 1984; Einsele *et al.* 1994; Dürr 1996), these two units are ubiquitously in tectonic contact and have recently been interpreted as separate terranes (Aitchison *et al.* 2000, 2002a).

A tectonic sliver of intra-oceanic island arc rocks (Zedong terrane) crops out between Lhasa and Dazhuqu terranes near Zedong and Luobusa. This terrane is bounded by north-directed thrusts related to the Renbu–Zedong thrust system of Yin *et al.* (1994). The basal contact of the section lies at a fault and begins with a thin (several metres) succession of arc tholeiitic lavas overlain by a *c.* 15 m sequence of red ribbon-bedded chert followed by 1000 m or more of volcaniclastic breccias. The succession is cut by numerous basaltic–andesite dykes and minor intrusions of diorite and leucogranite (McDermid *et al.* 2001a). Both radiometric and biostratigraphic data indicate the onset of magmatism in late Mid-Jurassic time. Radiometric ages determined by U/Pb ion microprobe zircon analysis together with $^{40}Ar/^{39}Ar$ ages for hornblende (McDermid *et al.* 2001b, 2002) are in accord with radiolarian faunas of Bajocian–early Callovian age in the underlying chert. The terrane is interpreted as remnants of intra-oceanic magmatic arc (Aitchison *et al.* 2000, 2002a; McDermid *et al.* 2001a) similar to other terranes known from elsewhere along the suture in NW India and Pakistan.

The Dazhuqu terrane consists of a series of ophiolitic bodies traceable along the Yarlung–Tsangpo suture zone with a major zone of outcrops near Xigaze (Aitchison *et al.* 2003). In this area the ophiolite is thrust northwards over the Xigaze terrane (Burg 1983; Wang *et al.* 1987). The southern margin of the terrane is defined, in many areas, by the Miocene north-directed Renbu–Zedong thrust (Yin *et al.* 1994, 1999), which places Indian Plate rocks over the ophiolite. In the Bainang district, where there is a sigmoidal bend in the Yarlung–Tsangpo suture zone, earlier contacts with the Bainang terrane can be observed at south-directed thrusts that are in places truncated by strike-slip faults (Girardeau *et al.* 1985a; Ratschbacher *et al.* 1994).

Several ophiolitic massifs in the Xigaze area form a nearly continuous belt over 175 km long and up to 25 km wide. Ophiolitic sections are mostly north-side up with the sequence repeated across dextral strike-slip faults. Although tectonically disrupted and heavily attenuated, sections locally display a complete ophiolitic sequence from fresh Cr diopside-rich harzburgites to marine sedimentary cover on mafic volcanic rocks (Nicolas *et al.* 1981; Girardeau *et al.* 1984, 1985a, 1985b). Aitchison *et al.* (2000, 2002a) interpreted the Dazhuqu terrane ophiolite as having originated in an intra-oceanic supra-subduction zone setting and this is supported by detailed mineralogical and geochemical studies in the Xigaze area (Hébert *et al.* 2000, 2001). Palaeomagnetic study of the sedimentary succession overlying mafic rocks of the Dazhuqu terrane indicates its deposition in an equatorial area, 1000–1500 km south of Asia's margin (Abrajevitch *et al.* 2001).

The Bainang terrane, on the southern side of the suture zone, was recently discriminated by Aitchison *et al.* (2000), who interpreted it as a subduction complex. The terrane lies between ophiolitic rocks of the Dazhuqu terrane to the north and the Indian terrane to the south. It contains units previously referred to as infra-ophiolitic thrust sheets of radiolarites (Burg & Chen 1984) or Upper Jurassic to Lower Cretaceous red radiolarites (Girardeau *et al.* 1984). Good exposures exist near Donglha, Xialu and Bainang. In most sections studied the terrane is chert dominated and is characterized by an overall south-younging tectonic pile of oceanic lithologies in which north-younging successions are stacked by a series of south-verging thrusts. Radiolarians reported from siliceous rocks near Xialu range in age from Mid-Jurassic to Early Cretaceous (Aptian) (Wu 1993; Matsuoka *et al.* 2001, 2002). Our detailed geological mapping and investigations of radiolarian biostratigraphy elucidate the structure, stratigraphy and evolution of the terrane (Ziabrev *et al.* 2000; Ziabrev 2002). Radiolarians allow reconstruction of a relict stratigraphy that records a long history of sedimentation in different portions of Tethys since the Late Triassic. Stratigraphy within the terrane records the northward travel of an oceanic plate and its approach towards a south-facing intra-oceanic subduction zone where accretion occurred from late Aptian to at least the Campanian (Ziabrev 2002). Variations in structural style across the terrane indicate deformation at different depths and vertical growth of the wedge dominant over lateral accretion. Tectonostratigraphic features specific to the Bainang terrane reflect its development in a remote intra-oceanic setting (Ziabrev 2002).

Passive margin rocks of the Indian terrane or Tethyan (Tibetan) Himalaya lie south of the suture. Thick Permian to Paleogene continental rise deposits (Liu & Einsele 1994) merge southward into a continuous Ordovician to Eocene shelf sedimentary succession of marine carbonates, sandstone, siltstone and shale (Bureau of Geology and Mineral Resources of Xizang Autonomous Region 1993; Jadoul *et al.* 1998). Disruption of northern Indian margin rocks into widespread regional mélange zones accompanied Paleogene collision between an intra-oceanic island arc and the northern margin of India (Liu *et al.* 2000; Liu & Aitchison 2002). Passive margin sedimentation finally ceased with the Cenozoic India–Asia collision.

The original disposition of terranes within the suture zone has been greatly disrupted and former relations between terranes are not well constrained, making reconstruction of the tectonic evolution of the area difficult. Most early models (Allègre *et al.* 1984; Searle *et al.* 1987) invoked the existence of a single Andean-type convergent plate margin along the northern side of Tethys, although the possibility of additional subduction zones was considered by some workers (Proust *et al.* 1984). The co-occurrence and north–south distribution of the Zedong (magmatic arc), Dazhuqu (forearc ophiolite) and Bainang (subduction complex) terranes led to their interpretation as evidence for a south-facing intra-oceanic subduction system that lay within the Tethys (Aitchison *et al.* 2000), and the existence of more than one convergent margin. Analogy with the modern western Pacific and SE Asia suggests that reality may have been even more complex. As more details and constraints on the evolution of terranes within the Yarlung–Tsangpo suture zone become available the complexity and sophistication of models for this zone is likely to increase.

Previous work

Most of the marine siliceous and fine-grained clastic deposits that cover the ophiolite crop out along the northern margin of the Dazhuqu terrane. These deposits are referred to as the Chongdu Formation (Cao (1981) cited by Bureau of Geology and Mineral Resources of Xizang Autonomous Region 1993). The first litho- and biostratigraphic information became available in reports of Sino-French expeditions to this area in the early 1980s (Marcoux *et al.* 1982; Girardeau *et al.* 1984, 1985a, 1985b). Previously the cherts as well as fine-grained clastic deposits have been accorded late Albian and possibly early Cenomanian ages based on radiolarians (Marcoux *et al.* 1982). Other radiolarian fossils described from these deposits were interpreted as being of late Albian to early Cenomanian age (Li & Wu 1985) or of early Cenomanian age (Wu 1986) based on correlation with the *Archaeospongoprunum techamaensis* Zone (Pessagno 1976) of California. As the precision of Upper Mesozoic radiolarian biostratigraphy has greatly improved since these pioneering studies it is now possible to reassess the biostratigraphy and sedimentary evolution of the Dazhuqu ophiolitic terrane. Radiolarian ages from deposits immediately overlying the ophiolite should constrain the timing and duration of the ophiolite generation event.

Methods

The sedimentary cover of the ophiolite has been studied at seven sections (Fig. 2) in the Xigaze area, most of which were reported by Sino-French expeditions to this area in the early 1980s (Girardeau *et al.* 1984). A detailed log was made of each section. Special attention was paid to the nature of contacts between pillow basalt or breccia and overlapping deposits, to recognize any tectonic disruption. Seventy-five samples were collected for micropalaeontological investigation and treated in dilute HF ± HCl to extract radiolarians. Species identification and age assignments are chiefly based on recent taxonomic studies and biostratigraphic zonation of Mid-Cretaceous Tethyan radiolarians (Jud 1994; O'Dogherty 1994). The first and last occurrences of some species are derived from an unpublished composite range chart of O'Dogherty snf Jud (O'Dogherty & Guex, pers. comm.). These range charts utilize the Unitary Association (UA) method (Guex 1991), and numerical UA ages calibrated to the Gradstein *et al.* (1994) time scale are applied herein. Over 50 radiolarian-based ages were thus acquired in the course of this study. To test the appropriateness of the western Tethys Mid-Cretaceous radiolarian range chart (O'Dogherty 1994) to our far eastern Tethyan study area as many taxa as possible were identified from each sample. The absence of unexpected co-occurrences indicates no detectable diachroneity in the distribution of taxa between western and eastern Tethys regions, suggesting that the range chart of O'Dogherty (1994) is applicable all along the Tethys.

Stratigraphy

Sedimentary sections exposed along 175 km strike length of the ophiolite were examined in detail. The sections are either situated along the northern boundary of the Dazhuqu terrane (Donglha-1, Polio and Dazhuqu) or tectonically interleaved within the ophiolite (Donglha-2, Qunrang and Zagapu) (Fig. 2). Various marine sedimentary lithologies overlie the ophiolite and include chert, siliceous mudstone and fine-grained volcaniclastic rocks. Exposure is near-continuous, with the uppermost levels of sections truncated by faults. Minor normal faulting within sections has locally eliminated small portions of some sections. Undisturbed depositional contacts with underlying pillow lavas or pillow breccias were recognized in most sections, although some minor shearing locally occurs near the contact. Sections adjacent to the Xigaze terrane are everywhere in fault contact with turbiditic rocks of the Xigaze Group.

Near the village of Donglha, 50 km SW of Xigaze a well-exposed section (Donglha-1, 29°08.392′N, 088°24.575′E) crops out on a hill slope beside an irrigation canal. Purplish red bedded (4–12 cm) chert is the dominant lithology although some intercalated (2–5 cm) chert and siliceous mudstone occurs at the top of the section. Sparse tuffaceous laminae and thin (0.5–4 cm) layers of felsic tuff become more abundant up-section. The chert depositionally overlies basaltic pillow breccia, the uppermost 20 cm of which is encrusted by massive chert. Two thin (5 cm) chert layers occur within the pillow breccia, 3 m and 6 m below the contact. The lower portion (14 m) of the chert crops out in a steeply north-dipping to vertical east–west-trending succession. Small-scale (tens of centimetres) south-verging intrafolial asymmetric folds indicate south-directed thrusting with a dextral strike-slip component. The upper portion of the sequence is folded and separated from lower parts of the section by 10 m of non-exposure. Many samples yielded abundant and well-preserved radiolarians (Table 1; Fig. 3) that allow precise age determination. The lower chert (samples 2–7) ranges from upper Barremian (UA1 *H. asseni* Zone) to lower Aptian (UA5/6 *H. verbeeki* Subzone) and both the upper and folded cherts (samples 7–20) are upper Aptian (UA6/7 to UA8 *T. costata* Subzone). The total range of the Donglha-1 section (*c.* 16 m thick) is upper Barremian to upper Aptian.

A tectonic sliver (100 m thick) of purplish red and greenish grey siliceous mudstones with minor greenish grey chert (Donglha-2, 29°06.954′N, 088°25.518′E) crops out 4 km SE of Donglha-1. This section is bounded by north-directed thrusts and structure is complicated by folds and shear zones with the possibility of tectonic repetitions, making it difficult to establish the original stratigraphy. Ten samples were collected and most possess similar radiolarian assemblages. Three assemblages with the widest stratigraphic range are used for correlation.

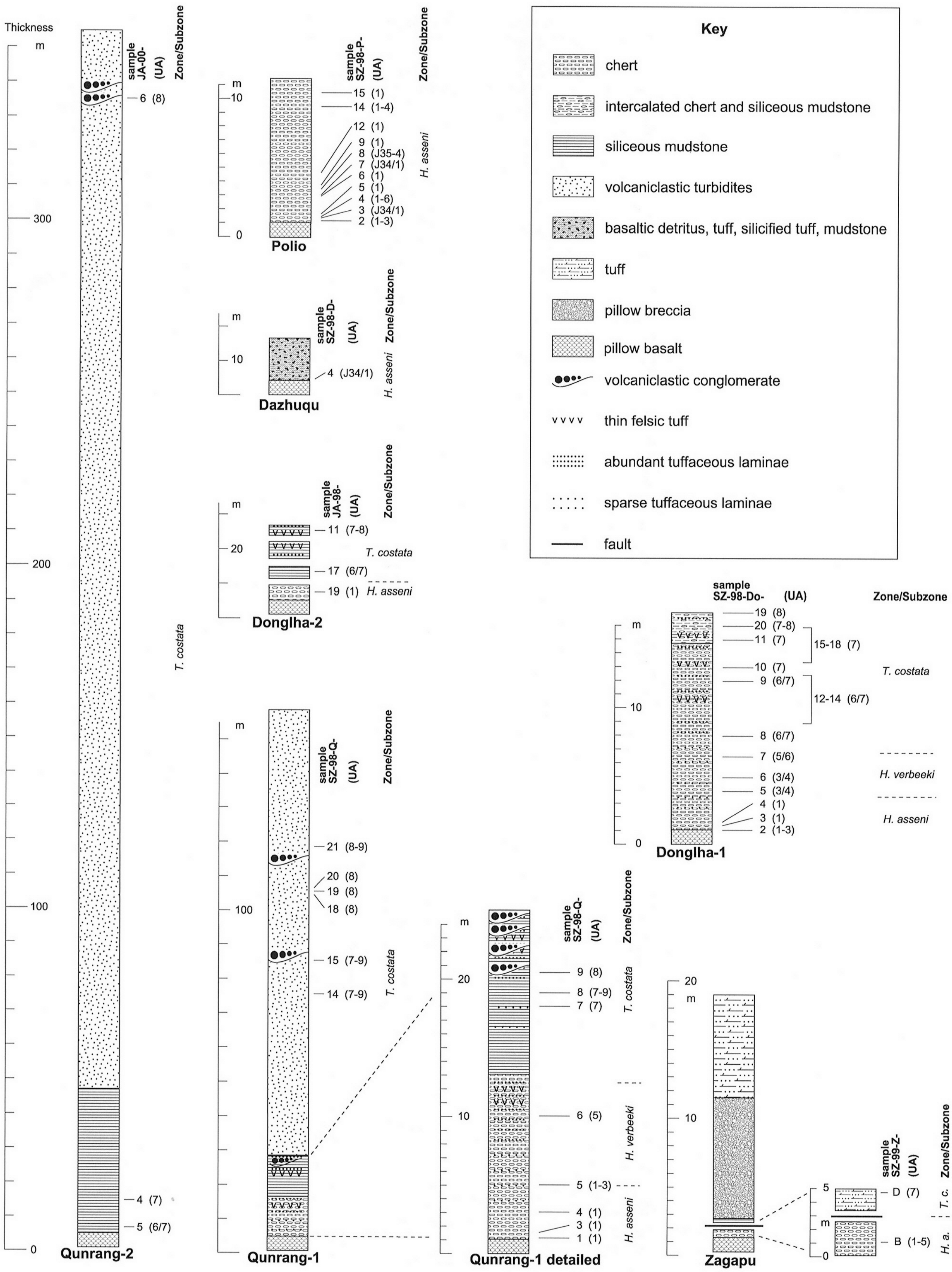
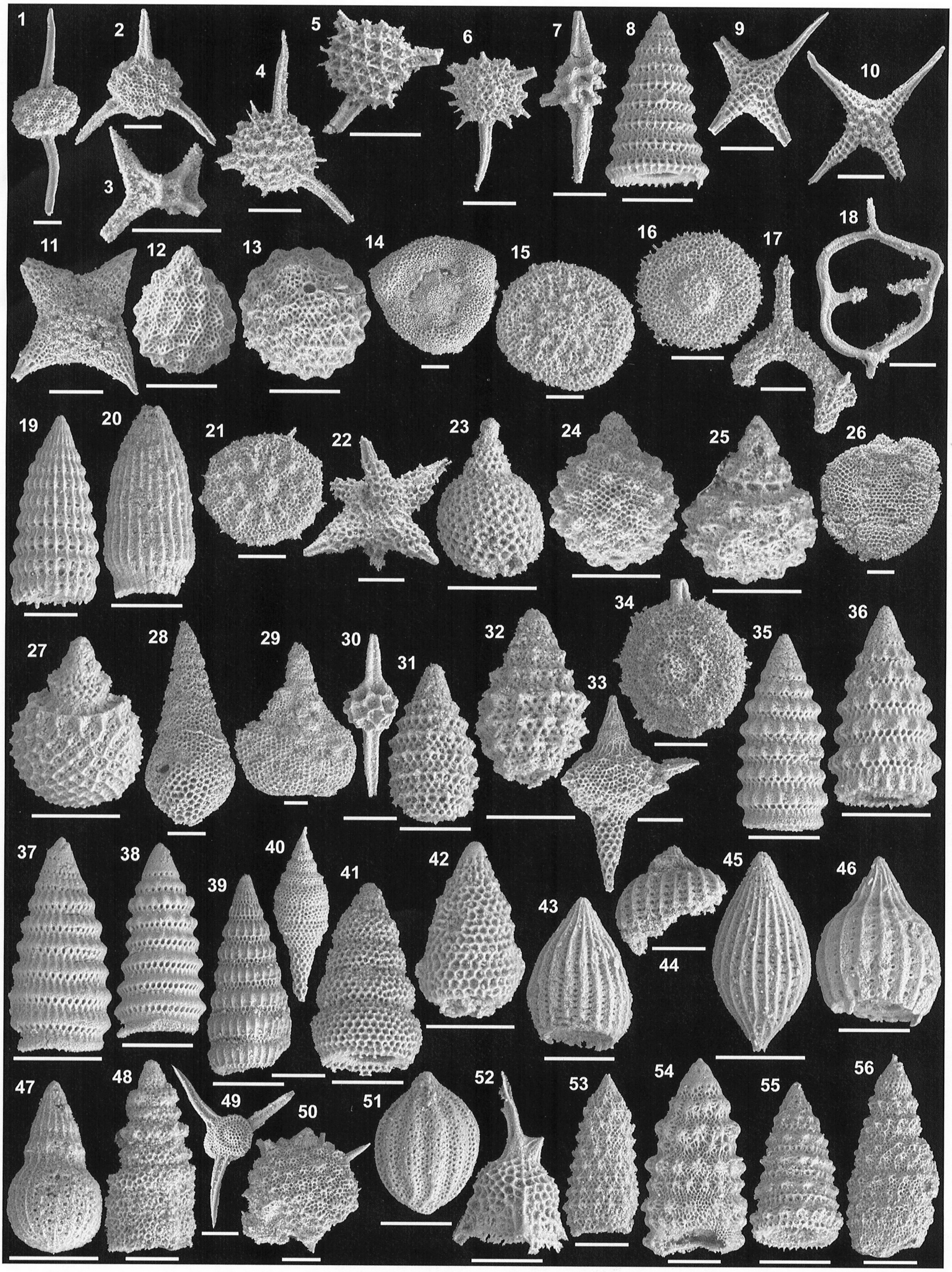


Fig. 2. Lithological columns of the sedimentary sections overlying pillow breccia of the Dazhuqu terrane, with the positions of samples and their correlation with Unitary Associations (UA) and zones or subzones. Details of some sections or their lower portions are shown at a larger scale on the right.

Table 1. *Occurrence of radiolarian species in the Dazhuqu terrane and the ages of radiolarian assemblages with respect to Unitary Associations*

sample number	SZ-98-Do-																			JA-98-			SZ-98-Q-														JA-00-			SZ-99		SZ-98-P-											SZ-98-D-4
species list	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	19	17	11	1	3	4	5	6	7	8	9	14	15	18	19	20	21	5	4	6	Z-B	Z-D	2	3	4	5	6	7	8	9	12	14	15	
Acaeniotyle diaphorogona Foreman		●	●		●	●	●	●	●	●	●	●	●		●	●	●	●	●	●					●	●	●												●		●	●	●		●			o					●
Acaeniotyle umbilicata (Rüst)	●	●	●		●	●	●	●	●	●	●	●	●		●	●	●	●	●		●	●	●		●	●	●	●						●	●				●		●	●	●		●		●			o	●	●	●
Aurisaturnalis carinatus (Foreman)																							●	●	●																												
Becus gemmatus Wu		●	●			●	●	●	●			●	●		●	●			●						●														●				●									●	
Becus helenae (Schaaf)				o																					●																	o	●		●	●	●	●	o	o	●	●	●
Becus horridus (Squinabol)									●	o	●		●		●	●	●	●																																			
Cecrops septemporatus (Parona)																																																					o
Crolanium puga (Schaaf)						●	●		●	●	●	●	●	●		●	●	●	●	o					●	●	●								●		●		●	●	●	●	●	●	●		●		●			●	●
Crucella bossoensis Jud																									●																		●								●		
Crucella euganea (Squinabol)							●	●	●	●	●	●	●		●	●	●	●	●																				●		●												
Crucella gavalai O'Dogherty				●	●	●	●	●			●	●	●																																								
Crucella hispana O'Dogherty																	●	●	●			●						o	●	●		o					●	●	●		●												
Cryptamphorella clivosa (Aliev)	●	●	●	●	●		●	●					●	●	●	●	●			●			●	●	●		●	●										●			●	o	o	●	●		●		●		●	o	●
Cryptamphorella crepida O'Dogherty	●				●																					●																								●		o	
Cryptamphorella gilkeyi (Dumitrica)																																								●													
Cyclastrum infundibuliforme Rüst																									●																												
Dactyliodiscus lenticulatus Jud			●	●				●	●	●	●	●		●	●		●		●						●	●			●																							●	
Dactyliosphaera maxima (Pessagno)								●		●				●	●	●	●	●	●		●																●	●	●														
Deviatus diamphidius (Foreman)						●		●	●	●			●						●		●	●			●																●		●								●		
Dicerosaturnalis amissus (Squinabol)			●	●		●	●	●	●	●	●	●			●	●	●								●																		●				●					●	●
Dictyomitra communis (Squinabol)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	o	o	●	●	●	●	●	●	●	●		●		●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●
Dictyomitra excellens (Tan)						●																			●																												
Godia decora (Li et Wu)							●	●	●	●	●	●	●	●	●	●	●	●	●		●	●						●	●	●							●	●	●		●												
Hexapyramis pantanellii Squinabol										o												●								●									●		●												
Hiscocapsa asseni (Tan)	●				●	●	●	●		●				●			●						●		●		●												●				●								●	●	
Hiscocapsa grutterinki (Tan)						●				●				●																									●				●			o							
Hiscocapsa kaminogoensis (Aita)																																											●				●						●
Hiscocapsa orca Foreman			–																	●			●																						●	●	●		●	●			
Hiscocapsa uterculus (Parona)																									●															●			●		●	o							●
Obeliscoites perspicuus (Squinabol)			●							●						●							o							o						●																	
Obeliscoites vinassai (Squinabol)							●																																		●												
Pantanellium lanceola (Parona)						●							●							●			●	●	●	●																●	●				●			●	●	●	
Parvicingula boesii (Parona)																							●	o																●		●	●		●	●	●		o	●			●
Parvicingula usotanensis Tumanda																							o	o																					●								●
Podobursa typica (Rüst)																									●																		●		●						●		
Podobursa tytthopora (Foreman)																							–		●																						●						
Pseudoaulophacus (?) *florealis* Jud		o																					●	●	●																				●							●	●
Pseudodictyomitra carpatica (Lozyniak)	●		●		●															o			●	●	●	●	●													o		o				o	●				o	●	●
Pseudodictyomitra hornatissima (Squinabol)		●				●	●	●		●	●	●	●		●	●	●	●	●				o	●			●	●	●	o	●	●		●	●	●	●	●	●			o	o	●	●		o						●
Pseudodictyomitra leptoconica (Foreman)	●																								●																	●		●	●	●	●	o	o	o	o	●	●
Pseudodictyomitra lilyae (Tan)	●																								●																			●									●
Pseudodictyomitra pentacolaensis Pessagno																		●															●	●	●	●			●														
Pseudoeucyrtis hanni (Tan)	●	●	●			●	●		●	●	●	●	●	●	●		●	●	●		●		●		●		●		●	●		o				●			●		●	o	o								o		●
Spongostichomitra elatica (Aliev)																														●						●																	
Staurosphaeretta longispina (Squinabol)												●				●		●																																			
Stichomitra communis Squinabol									●																		●							●	●				o														
Stichomitra mediocris (Tan)						●	●	●	●																			●																									
Thanarla brouweri (Tan)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●				●	●		●		●			●	●	●	●	●	●	●	●	●			●	●	●		●			●			●	●
Thanarla carboneroensis O'Dogherty																							●		●																												
Thanarla lacrimula (Foreman)	●	●	●	o	●	●														●	o		●	●	●	●	●													o		o	●		o		o				●	●	o
Thanarla pacifica Nakaseko & Nishimura	●	o	●	●	●	●							o							●			●	●	●	●	●										●			●		●	●	o	●	o	●	●		o			
Thanarla pseudodecora (Tan)	●		●																				●	●	●	●																	●								●	●	
Torculum bastetani O'Dogherty							●	●	●	●	●	●	●	●	●	●	●	●	●		●										●						●		●		●												
Triactoma echiodes Foreman						●	●	●		●	●	●			●	●								●																			●					●					●
Triactoma hybum Foreman			●			●	●	●	●	●	●	●	●		●	●				●					●		●																●										
Trisyringium capellinii Vinassa										●		●			o																										●												
Turbocapsula costata (Wu)						●				●	●	●			●	●	●	●	●		●	●						●	●	●				●	●		●		●		●												
Ultranapora praespinifera Pessagno						●	●	●		●	●	●	●	●	●	●	●	●	●						●					o																							
Xitus alievi (Foreman)	●	●	●	●	●															●			o	●	●	●																●	●		●		●			●			●
Xitus clava (Parona)	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	o	●	o	●	●	●	●	●		o				●	●		●	●	●	●	●	●	●	●	●	●	●			●		●	●
Xitus elegans (Squinabol)			●	●	●	o	●	●	o	●		●	●	●	●			●		●							●						●						●						●	●					o	●	
Xitus spicularius (Aliev)																					●	●											●	●				●	●		●												
Unitary Association (UA)	1-3	1	1	3/4	3/4	5/6	6/7	6/7	7	7	6/7	6/7	6/7	7	7	7	7	8	7-8	1	6/7	7-8	1	1	1	1-3	5	7	7-9	8	7-9	7-9	8	8	8	8-9	6/7	7	8	1-5	7	1-3	J34/1	1-6 (J35)	1	1	J34/J35 (J34/1)	J35-4	1	1	1-4	1	J34/J35 (J34/1)

●, species identified with certainty; ○, species identified with some doubt; Unitary Association numbers 1–9 refer to the biozonation of O'Dogherty (1994) and J34, J35 to that of Jud (1994); 1–3 indicates that the sample ranges from UA1 to UA3, 6/7 indicates that the sample lies between UA6 and UA7; sample series SZ-98-Do-, JA-98-, SZ-98-Q-, JA-00-, SZ-99-Z-, SZ-98-P- and SZ-98-D- are collected from sections Donglha-1, Donglha-2, Qunrang-1, Qunrang-2, Zagapu, Polio and Dazhuqu, respectively.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The succession ranges from upper Barremian (chert, sample 19; UA1 *H. asseni* Zone) to upper Aptian (sample 11; UA7-8 *T. costata* Subzone).

A steeply dipping north-younging sedimentary succession (Qunrang-1, 29°09.303′N, 089°02.702′E) conformably overlies pillow breccias within the ophiolite section on the hillside above the village of Qunrang. Three lithostratigraphic units are recognizable: purplish red bedded (2–7 cm) chert (12 m), purplish red siliceous mudstone (12 m) and thin-bedded (5–20 cm) fine- to medium-grained volcaniclastic turbidites (130 m). Chert and siliceous mudstone contain tuffaceous laminae and thin (0.5–3 cm) layers of felsic tuff, sparse at the bottom and abundant at the top (Fig. 2). Sand-sized lithic fragments in the turbidites are mostly of basaltic to andesitic composition. Four matrix-supported conglomerates (0.2–1.3 m) composed mostly of basalt and less abundant chert clasts sourced from underlying rocks occur in the upper portion of siliceous mudstone. Two clast-supported conglomerates (tens of centimetres) of similar composition lie within turbidites. Outcrop-scale asymmetric folds indicate south-directed thrusting with a sinistral strike-slip component. Rare layer-parallel shear zones traverse the section. To the north, the succession is faulted against a further section of ophiolitic basalt. Abundant well-preserved radiolarians indicate that the Qunrang-1 section ranges from uppermost Barremian to upper Aptian. Chert samples range from upper Barremian (UA1 *H. asseni* Zone) to lower Aptian (UA5 *H. verbeeki* Subzone). Overlying siliceous mudstones and volcaniclastic turbidites are upper Aptian (*T. costata* Subzone).

The thickest section (Qunrang-2, 29°08.750′N, 089°01.723′E) of purplish red siliceous mudstone (40 m) and overlying thinly bedded, fine- to medium-grained volcaniclastic turbidites (310 m) crops out 2 km SW of Qunrang-1. It rests conformably on basaltic pillow breccia and dips 55° SSW. Turbiditic sandstones are lighter in colour and appear more felsic than in the previous section. Some volcaniclastic conglomerates and thick devitrified tuffs occur near the top of the turbidites. The section above the conglomerates is intensely disturbed and folded in the footwall of a north-directed thrust where it is in contact with ultramafic rocks to the south. The entire sequence is assigned to the upper Albian (*T. costata* Subzone).

A thin sequence (Zagapu, 29°09.113′N, 089°15.419′E) of chert, tuff and siliceous mudstone within a pile of pillow breccia (>300 m thick) conformably overlain by 30 m of tuff is exposed near Zagapu village along the road from Bainang to Zagapu. Siliceous rocks (4 m thick) occur 40 m below the tuff and dip 70–85° NW. Dark grey to purplish red thinly bedded chert (2.5 m) conformably overlies pillow breccia. Above a shear surface, the chert is overlain by tuff (1.35 m) covered by thin (0.2 m) red siliceous mudstone, which is succeeded by pillow breccia. Two radiolarian assemblages recovered indicate that the chert (sample B) is upper Barremian–lower Aptian (UA1–5 *H. asseni* Zone to *H. verbeeki* Subzone) and the siliceous mudstone (sample D) is upper Aptian (UA7 *T. costata* Subzone).

Four kilometres south of the road from Lhasa to Xigaze in a creek near the village of Polio, a steeply south-dipping overturned sequence (Polio, 29°17.096′N, 089°25.286′E) of cherts (10.5 m) depositionally overlies pillow breccia. Although minor layer-parallel shearing is present it does not affect the contact. The northern limit of the sequence is tectonically juxtaposed against strongly sheared turbidites of the Xigaze terrane. Black and dark grey chert (0.9 m) above pillow breccia becomes pale grey up-section where individual chert beds (2–10 cm) are commonly separated by sepiolitic layers (3–10 cm), especially abundant between 4 and 9 m above the base. Abundant and moderately well-preserved radiolarians indicate that the lower 2.1 m of chert (samples 1–7) is upper Barremian (UA J34/J35 or J34/1).

Four hundred metres upslope from Dazhuqu village, 3 km south of the road from Lhasa to Xigaze, a 10–12 m thick sequence (Dazhuqu, 29°18.828′N, 089°32.058′E) of laminated greenish grey tuffs and reworked basaltic material (3–15 cm) depositionally overlies pillow breccia. Minor silicified tuff and mudstone (2–4 cm) and scarce bluish green chert (4 cm) occur together with fine-grained reworked basaltic detritus. The section is overturned and dips 65–80° south. No top to the sequence is exposed but nearby turbidites of the Xigaze terrane to the north are strongly sheared and folded, suggesting a tectonic contact with the Xigaze terrane. A radiolarian assemblage from the base of the sequence is upper Barremian (UA J34/J35 or UA J34/1).

Discussion

Well-preserved radiolarian faunas, thorough sampling and enhanced resolution of radiolarian biostratigraphy (Jud 1994; O'Dogherty 1994) allow reassessment of the ages of the sedimentary successions overlying the ophiolite and the accurate dating of sedimentary packages within these successions. This places important temporal constraints on the generation of the Dazhuqu terrane ophiolite and provides a basis for detailed sequence correlation (Fig. 4). The oldest deposits are well constrained as upper Barremian in sections at Polio, Dazhuqu, Donghla-1, Donghla-2 and Qunrang-1. The base of the Qunrang-2 section is upper Aptian. This indicates that eruption of ophiolitic basalt occurred before the late Barremian (*c.* 123 Ma in the Gradstein *et al.* (1994) time scale) to the late Aptian (*c.* 117 Ma). Although the pillow basalt–chert contact is diachronous throughout the terrane over a 175 km long zone of outcrop it appears that the sediments intercalated with, and immediately overlying, the ophiolitic basalts were deposited within a relatively short (i.e. <10 Ma) interval. With the exception of younger ages for sediments associated with basalts at Qunrang-2 and probably Zagapu, this event, along the length of the terrane, was completed within an even shorter (1–2 Ma) interval.

Investigation of supra-ophiolite deposits in the Yarlung Tsangpo suture zone provides a picture of the patterns of early sedimentation upon a newly built oceanic floor within an extensional zone that was part of an intra-oceanic subduction system. While the ophiolite was being generated deposition began with accumulation of pillow breccia several hundreds of metres thick. Development of pillow breccia probably occurred along the scarps of normal faults in this extensional setting. A few thin (5 cm) chert layers were deposited towards the end of pillow breccia accumulation. Background biogenic pelagic sedi-

Fig. 3. Radiolarians from the Dazhuqu terrane (scale bars represent 100 μm). 1, *Acaeniotyle umbilicata* (Rüst); 2, *A. diaphorogona* Foreman; 3, *Aurisaturnalis carinatus* (Foreman); 4, *Becus gemmatus* Wu; 5, *B. helenae* (Schaaf); 6, *B. horridus* (Squinabol); 7, *Cecrops* sp. cf. *C. septemporatus* (Parona); 8, *Crolanium puga* (Schaaf); 9, *Crucella euganea* (Squinabol); 10, *C. gavalai* O'Dogherty; 11, *C. hispana* O'Dogherty; 12, *Cryptamphorella clivosa* (Aliev); 13, *C. crepida* O'Dogherty; 14, *Cyclastrum infundibuliforme* Rüst; 15, *Dactyliodiscus lenticulatus* Jud; 16, *Dactyliosphaera maxima* (Pessagno); 17, *Deviatus diamphidius* (Foreman); 18, *Dicerosaturnalis amissus* (Squinabol); 19, *Dictyomitra communis* (Squinabol); 20, *D. excellens* (Tan); 21, *Godia decora* (Li & Wu); 22, *Hexapyramis pantanellii* Squinabol; 23, *Hiscocapsa asseni* (Tan); 24, *H. grutterinki* (Tan); 25, *H. kaminogoensis* (Aita); 26, *H. orca* Foreman; 27, *H. uterculus* (Parona); 28, *Obeliscoites perspicuus* (Squinabol); 29, *O. vinassai* (Squinabol); 30, *Pantanellium lanceola* (Parona); 31, *Parvicingula boesii* (Parona); 32, *P. usotanensis* Tumanda; 33, *Podobursa tytthopora* (Foreman); 34, *Pseudoaulophacus* (?) *florealis* Jud; 35, *Pseudodictyomitra carpatica* (Lozyniak); 36, *P. hornatissima* (Squinabol); 37, *P. leptoconica* (Foreman); 38, *P. lilyae* (Tan); 39, *P. pentacolaensis* Pessagno; 40, *Pseudoeucyrtis hanni* (Tan); 41, *Stichomitra communis* Squinabol; 42, *S. mediocris* (Tan); 43, *Thanarla brouweri* (Tan); 44, *T. carboneroensis* O'Dogherty; 45, *T. lacrimula* (Foreman); 46, *T. pacifica* Nakaseko & Nishimura; 47, *T. pseudodecora* (Tan); 48, *Torculum bastetani* O'Dogherty; 49, *Triactoma hybum* Foreman; 50, *Trisyringium capellinii* Vinassa; 51, *Turbocapsula costata* (Wu); 51, *Ultranapora praespinifera* Pessagno; 53, *Xitus alievi* (Foreman); 54, *X. clava* (Parona); 55, *X. elegans* (Squinabol); 56, *X. spicularius* (Aliev).

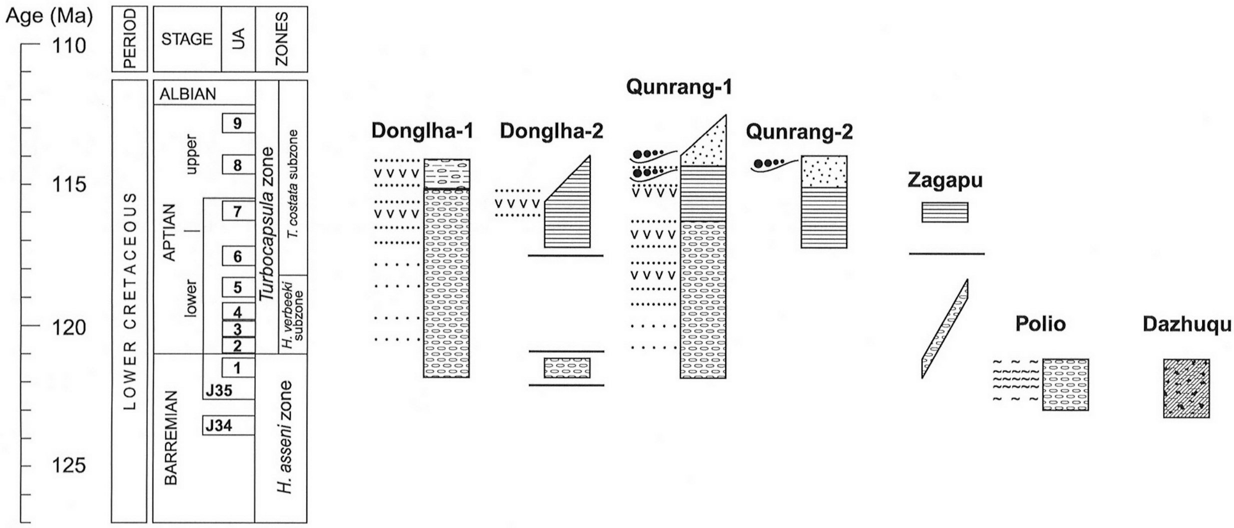

Fig. 4. Correlation chart of the Dazhuqu terrane radiolarian-bearing deposits with lithologies plotted against biostratigraphic (after O'Dogherty 1994; Jud 1994) and chronostratigraphic (after Gradstein *et al.* 1994) scales. Non-horizontal boundaries indicate uncertainties in age. (For key see Fig. 2.)

mentation was established along the terrane by the late Barremian after the cessation of pillow breccia development. In the easternmost sections, the earliest (late Barremian) accumulation of pelagic chert was swamped by deposition of glassy basaltic detritus that is now locally altered to sepiolite. In the central and western portions of the terrane, chert deposition continued until the late Aptian (Donglha-1) or had terminated by then (other sections). It was interrupted by ash falls from an adjacent volcanic arc and bottom traction currents that reworked tuffaceous materials. Pelagic sedimentation progressed into accumulation of hemipelagic siliceous mudstone in the late Aptian at Donglha-2, Qunrang-1 and Zagapu. At Qunrang-2, sedimentation started with deposition of siliceous mudstones in the late Aptian. The frequency of ash falls and activity of bottom traction currents varied through space and time. Hemipelagic sedimentation at Qunrang-1 was interrupted by deposition, from mudflows, of several matrix-supported conglomerates composed of basalt and chert clasts sourced from stratigraphically lower rocks. During the late Aptian, development of pillow breccia resumed at Zagapu, and later switched to thick tuff accumulation. At Qunrang, volcaniclastic turbidite sedimentation took over from hemipelagic sedimentation in the beginning of the late Aptian, when up to 300 m of fine- to medium-grained turbidites were deposited during a short period. The absence of carbonate deposits in the marine sedimentary veneer on the ophiolite indicates sedimentation below the carbonate compensation depth.

Sequences and ages of lithologies in the sedimentary succession vary between sections even where they are only separated by a few kilometres. We interpret such variations as a result of sediment accumulation in small semi-isolated basins on the ophiolitic basement. This is in accord with the interpretation of the ophiolite belt in the Xigaze area as a tectonic collage of individual massifs genetically related to locally different settings within an overall supra-subduction zone environment (Hébert *et al.* 2000, 2001). Sections in the western and central parts of the study area exhibit coarsening-upward tendencies, which is especially clear at Qunrang-1. The upper portion of this section (above the pillow breccia) documents a change from pelagic (chert) to hemipelagic (siliceous mudstone) and finally to volcaniclastic turbidite sedimentation. This marked coarsening up-section tendency probably reflects development of a sediment dispersal system associated with a volcanic arc and its progradation onto a zone of newly built supra-subduction zone oceanic floor. The basaltic to andesitic source of volcaniclastic turbidites in the Dazhuqu terrane differs from the source of the Xigaze terrane sandstones, which are considerably more felsic (Dürr 1996). Examinations of the sedimentology and radiolarian assemblages in sections overlying pillow basalts of the Dazhuqu terrane ophiolite indicate the rapid development of the ophiolite over a short mid-Cretaceous interval in a Tethyan intra-oceanic island arc setting isolated from any continental landmass such as that inferred to have existed within Tethys in the model of Aitchison *et al.* (2000).

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