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# Upper Jurassic Reefs from the Russian Western Caucasus: Implications for the Eastern Black Sea

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**Abstract:** Exposures of Upper Jurassic reef outcrops in the Russian western Caucasus provide excellent field analogues for possible reef-complex reservoir targets imaged on seismic reflection data from the northern Shatskiy Ridge, eastern Black Sea. The reefs at outcrop can be generally grouped into coral-dominated, siliceous sponge-microbialite and microbialite types. Coral-dominated reefs occur as isolated patchy and massive forms, and can be subdivided into higher-diversity and low-diversity types. The former developed at shallow-water platform margins and in platform interiors, whilst the latter occurred in deeper-water mid-shelf settings. Siliceous sponge-microbialite and microbialite reefs occur as lenses and mounds that were restricted to deeper-water mid-outer shelf environments. The reefs developed on two Late Jurassic carbonate platforms in the Russian western Caucasus: the north Caucasus platform to the north and South Adler platform to the south. These platforms were separated by a deep marine (Greater Caucasus) basin, along the margins of which thick shallow-water coral-dominated reefs formed. The southwestern margin of the north Caucasus platform probably represented a reef barrier-slope-basinal system that was structurally controlled. At the northeastern margin of this platform, in the Laba River region, inner ramp coral-dominated reefs pass northwards into deeper-water siliceous sponge- and microbialite-dominated reefs. The South Adler platform may extend offshore into the eastern Black Sea and the coral-dominated reefs that crop out at its northern margin form potential exploration analogues. The palaeowater depth of the possible isolated reef complexes imaged on the Shatskiy Ridge is unclear. If they were deposited in shallow-water, the coral-dominated reefs examined in the north Caucasus or South Adler carbonate platforms may form suitable analogues. Alternatively, if they were developed in deeper water they may be equivalent to the siliceous sponge and microbialite reefs examined in the Laba River region.

**Key Words:** Late Jurassic, carbonate platform, reefs, Russian western Caucasus, eastern Black Sea, Shatskiy Ridge, reservoir analogues

## Batı Kafkasya'nın Rus Kesiminde Geç Jura Resifleri

**Özet:** Batı Kafkasyanın Rus kesiminde yüzeyleyen Geç Jura yaşlı resif mostraları, doğu Karadeniz'de Shatsky sırtının kuzeyinde sismik yansıma kesitlerinde tespit edilen rezervuar özellikli, olası resif kompleksleri için iyi bir analoglar oluşturur. Resifler arazide, mercanlı, silisli-sünger mikrobiyolitli ve mikrobiyolitli olmak üzere üç tipe ayrılır. Mercanlı resifler izole veya massif şekilde bulunur ve çok çeşitli ve az çeşitli olmak üzere iki alt tipe ayrılabilir. Çok çeşitli mercan resifleri sığ platform kenarlarında veya platform içinde gelişmiştir, az çeşitli mercan resifleri ise daha derin suda, orta selfde oluşmuştur. Süngerli mikrobiyolitli ve biyolitli resifler daha derin sularda orta ve dış self ortamlarında gelişmiş mercanlar ve tepelikler yapar. Resifler batı Kafkasya'da iki farklı Jura platformunda gözlenir: kuzeyde Kuzey Kafkas Platformu ve güneyde Güney Adler Platformu. Bu iki platform derin denizel Büyük Kafkasya havzası ile ayrılmıştır; bu havza ile platformların sınırlarında sığ sularda mercanlarca zengin kalın resifler gelişmiştir. Kuzey Kafkas Platformunun güneybatı kenarı yapısal kontrollü bir mercan seti-yamacı-havzası ile tanımlanır. Aynı platformun kuzeydoğu kenarında, Laba nehri bölgesinde ise, mercanca baskın resifler kuzeye doğru daha derin koşullarda oluşmuş sünger mikrobiyolitli ve biyolitli resiflere geçer. Güney Adler Platformu denize Doğu Karadeniz'e doğru uzanabilir, ve platformun kuzey kenarında gözlenen mercan ağırlıklı resifler, doğu Karadeniz'de potansiyel hidrokarbon hedefleri oluşturabilir. Shatsky sırtı üzerinde sismik kesitlerde gözlenen muhtemel izole resif komplekslerinin ilksel çökme derinliği açık değildir. Eğer bunlar sığ sularda oluşmuşsa, kuzey Kafkas ve Güney Adler platformunda incelenen resifler bunlar için uygun analog oluşturabilir. Eğer Shatsky sırtında gözlenen resif kompleksleri derin sularda oluşmuşsa, bu resifler Laba Nehri bölgesinde incelenen silisli sünger ve mikrobiyolitli resiflere benzebilir.

**Anahtar Sözcükler:** Geç Jura, karbonat platform, resif, batı Kafkasya, doğu Karadeniz, Shatskiy sırtı, rezervuar analogları

## Introduction

Russian seismic data have recently revealed the possible presence of Upper Jurassic reef complexes up to 1–2 km thick and 10–20 km wide on the northern Shatskiy Ridge in the eastern Black Sea (Afanasenkov *et al.* 2005) (Figure 1). However, these features are deeply buried (>6000 m) and there are no data on what they are composed of, how they developed, and what their reservoir potential is likely to be. The aim of this paper is to investigate onshore Upper Jurassic reefs in the Russian western Caucasus as they form potential analogues for their possible offshore counterparts.

Long-term relatively high sea level during the Late Jurassic interval (Oxfordian–Early Tithonian) resulted in extensive reef development along the northern Tethys margin (Kiessling *et al.* 1999; Leinfelder *et al.* 2002). A reef belt occurs in Portugal, Spain, France, Switzerland, southern Germany, Poland, and Romania (Leinfelder 1993a, b; Leinfelder *et al.* 1993a, 2002; Aurell & Bádenas 1997; Insalaco *et al.* 1997; Pawellek & Aigner 2003; Benito & Mas 2006). This reef belt extends further into Crimea, the Great Caucasus and the Caspian region (Rostovtsev 1992; Kuznetsov 1993; Turov *et al.* 1999; Beznosov & Mitta 2000). Although a general description of the Upper Jurassic reefs in the Russian western Caucasus is available (Siderenko 1968; Sedleskii *et al.* 1977; Bendukidze 1982; Rostovtsev 1992; Kuznetsov 1993), little has been published in the international literature. Many aspects of the reefs, such as their composition, origin and facies associations have been barely studied. In addition, the stratigraphy, biostratigraphy, palaeogeographical setting and overall facies distribution of the Upper Jurassic succession in the Russian western Caucasus are poorly constrained, although a general illustration of the regional palaeogeographic setting has been presented (see Afanasenkov *et al.* 2005, 2007; Panov 2006; Ruban 2006).

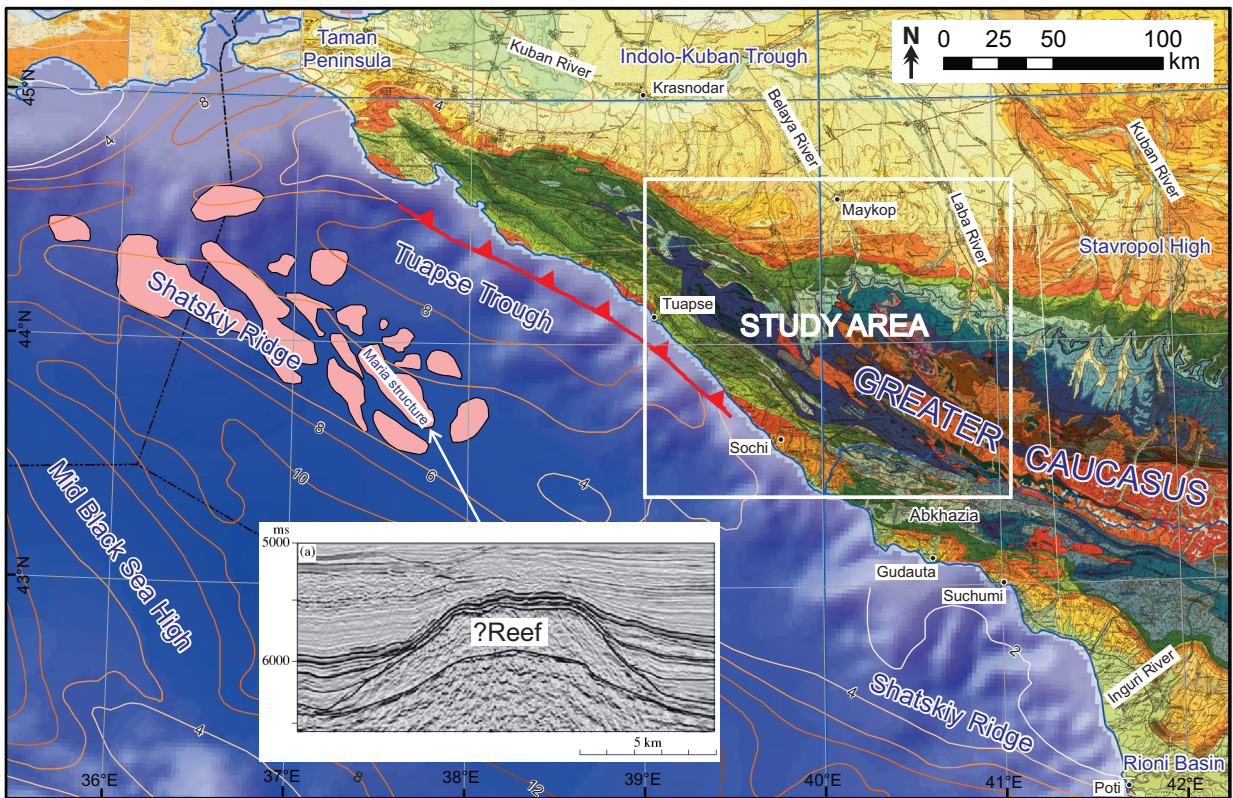
A revision of the existing Upper Jurassic stratigraphic and biostratigraphic framework for the Russian western Caucasus was beyond the scope of this study. Instead, its focus was the documentation of the field relationships and microfacies of the already mapped carbonate facies. The bulk of this paper comprises a detailed description of the different reef

types and components present and a discussion of their depositional environments and developmental processes. This is preceded by an overview of the geological setting, and stratigraphy and sedimentary facies of the Upper Jurassic succession in the Russian western Caucasus, based on our previous work (e.g., Lavrishchev *et al.* 2000, 2002), observations made during this study and the available geological literature. It is followed by a summary of the regional facies distribution in the study area and some conclusions and implications.

## Geological Setting

The Russian western Caucasus was situated close to the northern margin of Tethys during Jurassic time. North-directed subduction of Tethys generated a series of, most likely, transtensional and transpressional events that resulted in the formation and partial closure of a series of basins in the overriding Eurasian plate (Nikishin *et al.* 1998, 2001; Golonka 2004; Kaz'min & Tikhonova 2006; Saintot *et al.* 2006). These include the Greater Caucasus Basin that underwent rapid subsidence and intermittent bimodal rift-related volcanism during Early to early Middle Jurassic time (Lordkipanidze *et al.* 1989; Nikishin *et al.* 2001; Saintot *et al.* 2006; McCann *et al.* 2010) and whose sedimentary record is preserved south of the Greater Caucasus' crystalline core. Bathonian deformation and a shallowing-upward progression of facies (commonly referred to as the Middle Cimmerian orogeny; Nikishin *et al.* 2001) was preceded, on the southern side of the Caucasus, by the extrusion of large amounts of Bajocian subduction-related calc-alkaline basalts and andesites (Mengel *et al.* 1987; Nikishin *et al.* 2001; Saintot *et al.* 2006; McCann *et al.* 2010). This was probably driven by a shallowing of the northerly-subducting Neotethyan slab and resulted in an enlargement of the subduction-related arc previously centred in the Transcaucasus, an increase in compression stresses in the upper plate, and uplift and regression (Saintot *et al.* 2006; McCann *et al.* 2010).

Although Late Jurassic rifting has been suggested (e.g., Nikishin *et al.* 1998), field evidence for crustal extension in the Russian western Caucasus is limited and, instead, the gross bathymetric controls on carbonate facies development are thought to have



**Figure 1.** Geological map of the eastern Black Sea and the study area in the Russian western Caucasus. The depth (in km) to the base of the Cenozoic fill of the eastern Black Sea is from Meisner & Tugolosov (2003). The position of probable Upper Jurassic reef bodies on the Shatskiy Ridge (pink shapes) and a seismic line through the Mariya structure are from Afanassenkov *et al.* (2005).

been largely inherited from the partial inversion of earlier rift events. Regional subsidence was probably triggered by post-rift thermal subsidence in the Greater Caucasus Basin (Saintot *et al.* 2006) and/or a steepening of the Neotethyan subducting slab (McCann *et al.* 2010). Much of the Great Caucasus, Crimea and Pontides during Late Jurassic time represented a shallow epicontinental sea.

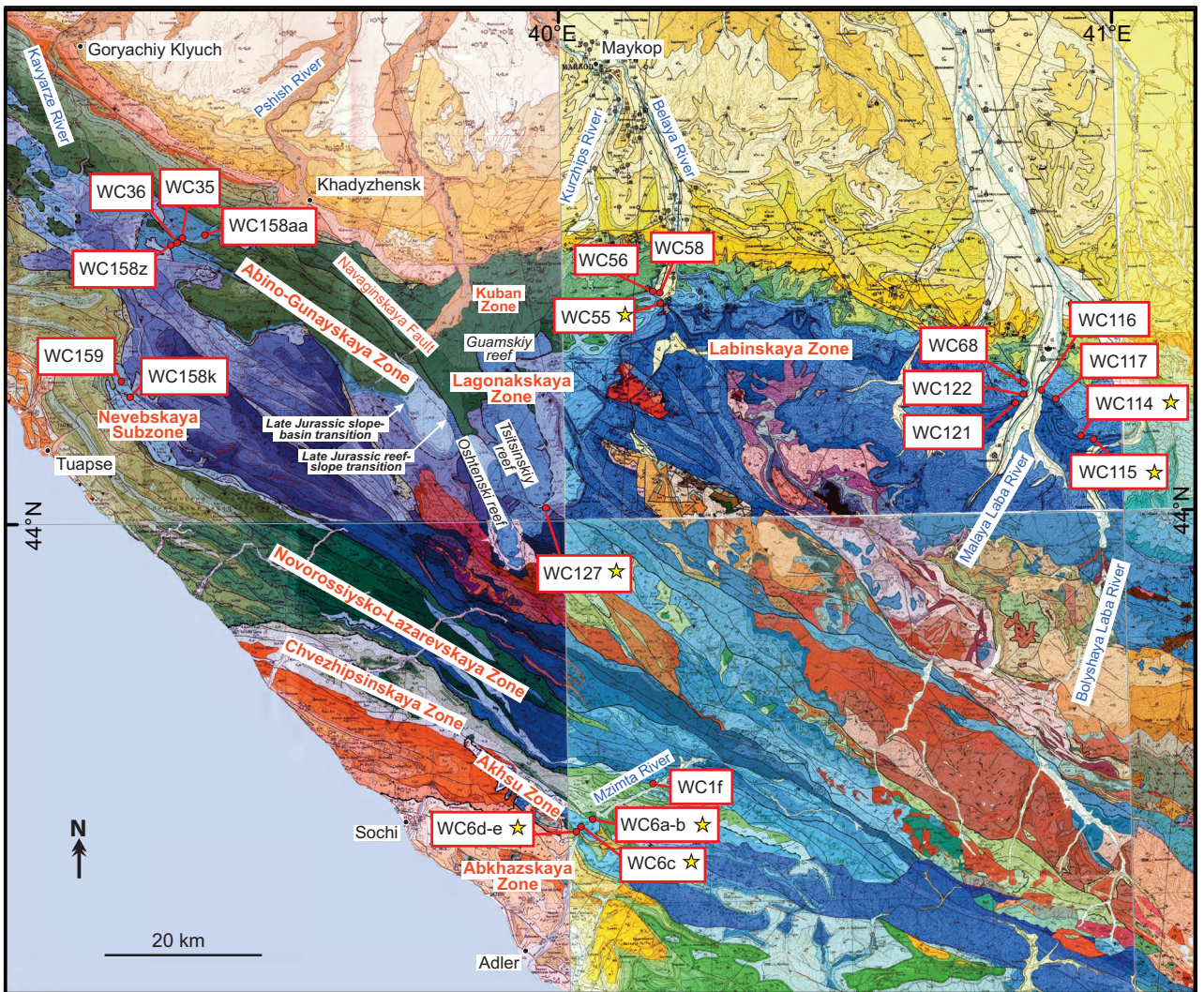
### Study Area and Methods

A number of key Upper Jurassic outcrops were examined in the Russian western Caucasus during this study (Figures 2 & 3, Table 1). Formation and age data were derived from existing geological mapping (e.g., Melnikov *et al.* 1994; Lavrishchev *et al.* 2000, 2002; Korsakov *et al.* 2002) (Figure 3). Microfacies analysis was carried out on 87 large thin sections of field samples using standard transmitted-light

microscopy. Thin sections were first impregnated with blue-dye stained resins and stained with a potassium ferricyanide/alizarin red-S solution (Dickson 1965).

### Stratigraphy and Sedimentary Facies

The Russian western Caucasus is divided into a number of tectonostratigraphic zones and subzones by local geologists, each with different Upper Jurassic stratigraphies (e.g., Rostovtsev 1992; Lavrishchev *et al.* 2000, 2002; Korsakov *et al.* 2002). Upper Jurassic outcrops were studied in six of these zones, with reefal facies being examined in the shallow-water Labinskaya (localities WC55, WC114, WC115 and WC121), Lagonakskaya (Lago Naki) (locality WC127) and Akhtsu (locality WC6a-e) zones at the margins of the Greater Caucasus Basin (Figures 2 & 3). Deeper-water facies within the Greater Caucasus Basin were examined in the Abino-Gunayskaya and



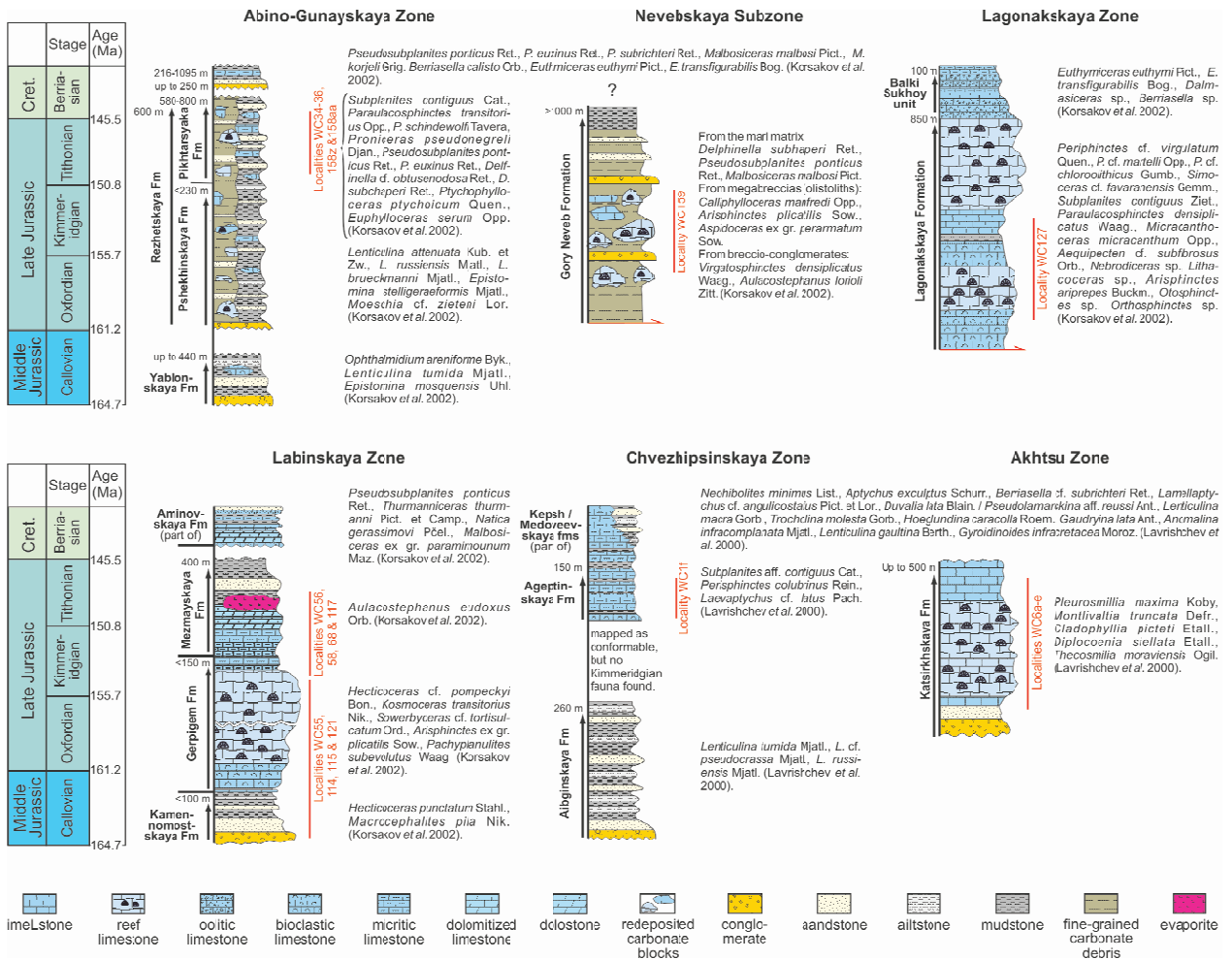
**Figure 2.** Position of Upper Jurassic study localities in the Russian western Caucasus. The geological map and tectonostratigraphic zone notation are from Melnikov *et al.* (1994), Lavrishchev *et al.* (2000, 2002) and Korsakov *et al.* (2002). Jurassic strata are highlighted in blue. The yellow stars indicate localities where Late Jurassic reefs were observed.

Chvezhipsinskaya zones, and Nevebskaya subzone. The following sections give an overview of the stratigraphy and facies of these six zones based on previous work and observations made during this study.

*Labinskaya Zone*

*Overview*– In the Labinskaya Zone, in the northeast of the study region, the Upper Jurassic succession comprises the Upper Callovian–Lower Kimmeridgian Gerpigem and Middle Kimmeridgian–Tithonian

Mezmayskaya formations (strictly speaking therefore, carbonate deposition spanned latest Middle to Late Jurassic time, although for simplicity, and in common with earlier works (e.g., Rostovtsev 1992), it is referred to as being Late Jurassic in age here). The Gerpigem Formation is reported to unconformably or conformably overlie Lower to Middle Callovian siliciclastic rocks of the Kamennomostskaya Formation (Rostovtsev 1992; Melnikov *et al.* 1994; Korsakov *et al.* 2002). According to Rostovtsev (1992), the basal sediments of the formation are characterized by limestone conglomerates/brecciated



**Figure 3.** Upper Jurassic stratigraphy, sedimentary facies and key fossil occurrences in the six tectonostratigraphic zones examined in this study (modified from Lavrishchev et al. 2000, 2002 and Korsakov et al. 2002). See Figure 2 for the tectonostratigraphic zone and study locality positions.

limestones up to 10 m thick that are overlain by a lower 25 m interval of detrital limestones and marls. The mid part of the formation is typically 65 m thick and comprises bioclastic limestones that in places contain isolated reefs up to 200–250 m thick. The upper part of the formation is up to 20 m thick and consists of fine-grained dolostones interbedded with dark grey mudstones. Rostovtsev (1992) described the Mezmayeskaya Formation as comprising a lower evaporitic unit, which is dominated by halite, gypsum and anhydrite with layers of multicoloured marls and clays, and an upper lagoonal clastic unit consisting of reddened and mottled silty clays, with limestones, marls and sandstones. The lower evaporitic unit thins

from east to west from 500 m thick in the Malaya Laba River catchment to pinch-out in the Kurzhips River catchment, whilst the upper lagoonal unit thins towards the east from 300 m thick in the Kurzhips River catchment to 40–50 m thick on the Kuban River.

*This Study*– The lower part of the Upper Jurassic succession, the Gerpigim Formation, was observed in high cliffs in the easternmost part of the study region, near the Bolyshaya Laba River at localities WC114 and WC115 (Figure 2). At both localities the formation would appear conformable with the underlying sandstone-dominated

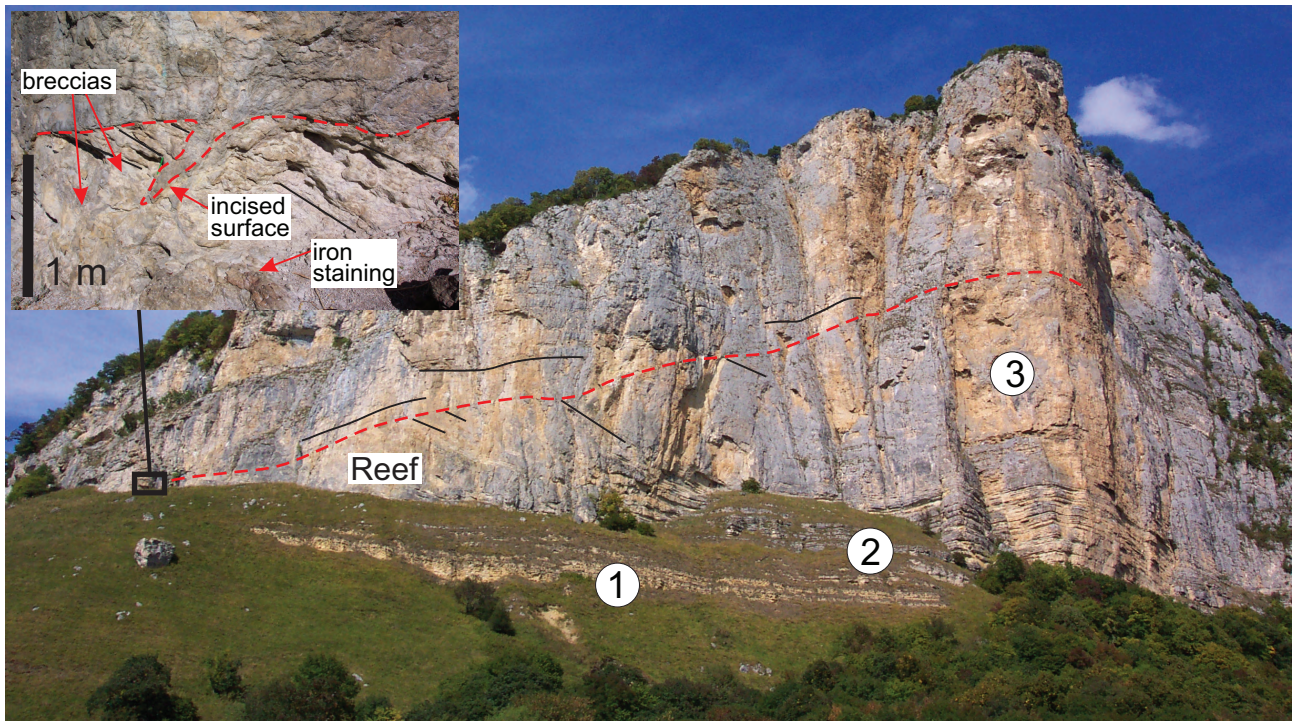
UPPER JURASSIC REEFS

**Table 1.** List of Upper Jurassic localities, Russian western Caucasus.

Locality	Latitude (N)	Longitude (E)	Formation	Presumed Age
WC1f	43°39.366′	40°09.317′	Ageptinskaya	Tithonian
WC6a	43°36.571′	40°02.814′	Katsirkhskaya	Oxfordian–Tithonian
WC6b	43°36.399′	40°02.547′	Katsirkhskaya	Oxfordian–Tithonian
WC6c	43°36.010′	40°01.518′	Katsirkhskaya	Oxfordian–Tithonian
WC6d	43°35.672′	40°01.128′	Katsirkhskaya	Oxfordian–Tithonian
WC6e	43°35.655′	40°01.058′	Katsirkhskaya	Oxfordian–Tithonian
WC35	44°22.300′	39°19.326′	Pikhtarskaya	Tithonian–Early Berriasian
WC36	44°21.730′	39°18.210′	Pikhtarskaya	Tithonian–Early Berriasian
WC55	44°16.860′	40°10.820′	Gerpigem	Late Callovian–Early Kimmeridgian
WC56	44°17.690′	40°09.990′	Mezmayskaya	Kimmeridgian–Middle Tithonian
WC58	44°14.000′	40°10.460′	Gerpigem- Mezmayskaya	Kimmeridgian
WC68	44°10.050′	40°49.850′	Mezmayskaya	Tithonian
WC114	44°05.900′	40°56.000′	Gerpigem	Late Callovian–Kimmeridgian
WC115	44°05.600′	40°57.200′	Gerpigem	Late Callovian–Kimmeridgian
WC116	44°09.643′	40°51.002′	Gerpigem	Oxfordian–Kimmeridgian
WC117	44°08.958′	40°51.443′	Gerpigem- Mezmayskaya	Kimmeridgian–Tithonian
WC121	44°08.579′	40°48.891′	Gerpigem- Mezmayskaya	Late Callovian–Tithonian
WC122	44° 09.243′	40°49.751′	Gerpigem- Mezmayskaya	Late Callovian–Tithonian
WC127	44°01.070′	39°58.297′	Lagonakskaya	Oxfordian–Kimmeridgian
WC158k	44°09.900′	39°13.650′	Gory Neveb	Oxfordian–Early Berriasian
WC158z	44°21.564′	39°17.813′	Pikhtarskaya	Tithonian–Early Berriasian
WC158aa	44°22.298′	39°21.170′	Pikhtarskaya	Tithonian–Early Berriasian
WC159	44°11.127′	39°12.698′	Gory Neveb	Oxfordian–Early Berriasian

Kamennomostskaya Formation. At locality WC115, the formation is up to ~150 m thick and comprises a basal unit of brown, bedded sandy limestones that grade up into grey-bedded bioclastic limestones and massive reef dominated limestones (Figure 4). No limestone conglomerates or brecciated limestones were observed. A patch reef, approximately 20 m thick and 20–40 m across, was examined in the lower part of the outcrop. This reef consists mainly of coral boundstones and is characterised by the occurrence of numerous open pores. The reef is overlain by bedded bioclastic limestones with coral

and other reef component fragments. The top of the bedded bioclastic limestones is marked by a major erosion surface with irregular incised features, iron-stained patches and breccias (Figure 4). This erosion surface has a local relief of around 70 m, implying a relative sea-level drop of at least this magnitude, most likely during Oxfordian time. Above the erosion surface, coral-dominated rudstones occur, indicating the existence of coral reefs nearby. The thickest, inaccessible part of the cliff, probably also contains reef facies.



**Figure 4.** The Middle to Upper Jurassic succession exposed near the Bolyshaya Laba River (locality WC115). The succession consists of brownish sandstones (1) at the top of the Lower to Middle Callovian Kamennomostskaya Formation, and grey sandy limestones (2) and thick-bedded to massive, cliff-forming shallow-marine platform carbonates with coral reef facies (3) in the ~150-m-thick Upper Callovian to Lower Kimmeridgian Gerpigem Formation. A major truncation surface is developed within the succession that displays evidence for subaerial exposure, incision, iron staining and brecciation (see insert).

The thickness of the Gerpigem Formation decreases towards locality WC114, 2 km to the west of locality WC115. Small, possible reef mounds (or bioherms) crop out between the localities. A large complex mound is exposed at locality WC114 (Figure 5). It is about 5–30 m high and 50 m long and consists mainly of siliceous sponge-microbialite and microbialite boundstones. The mound is made up of a cluster of much smaller lenticular bodies or bioherms. The top of the reef succession is capped by thinly-bedded microbialite floatstones and bioclastic limestones.

Further exposures of the Gerpigem Formation, as well as the overlying Mezmayaskaya Formation, crop out 10 km to the northwest of localities WC114–WC115 on the Malaya Laba River (localities WC68, WC116, WC117, WC121 & WC122) (Figure 2). In the most southerly exposures, to the west of locality WC121, massive possible reefs and intervening

bedded limestones are again exposed. These pass northward into chaotic, thick-bedded units composed of allochthonous blocks of reefal debris and other platform limestones within a marl and mudstone matrix (Figure 6). These are interpreted as debris and other gravity flow deposits. They grade laterally into more coherently bedded calciturbidite beds and represent north-facing slope deposits within the Gerpigem Formation. These slope deposits are overlain by thin-bedded, fine-grained brachiopod limestones and medium-bedded pinkish dolostones that pass up into massive anhydrites of the Mezmayaskaya Formation.

In the western part of the Labinskaya Zone, the Upper Jurassic succession was observed in steep cliffs at locality WC55 in the Belaya River gorge (Figure 7). Here, the Gerpigem Formation is conformable on a dramatically thinned (~7 m thick), mudstone-dominated Kamennomostskaya





**Figure 5.** The lower part of the Upper Jurassic succession exposed near the Bolyshtaya Laba River (locality WC114) forms a mound complex of smaller lenticular reef bodies composed mainly of siliceous sponge-microbialite and microbialite boundstones (see insert).



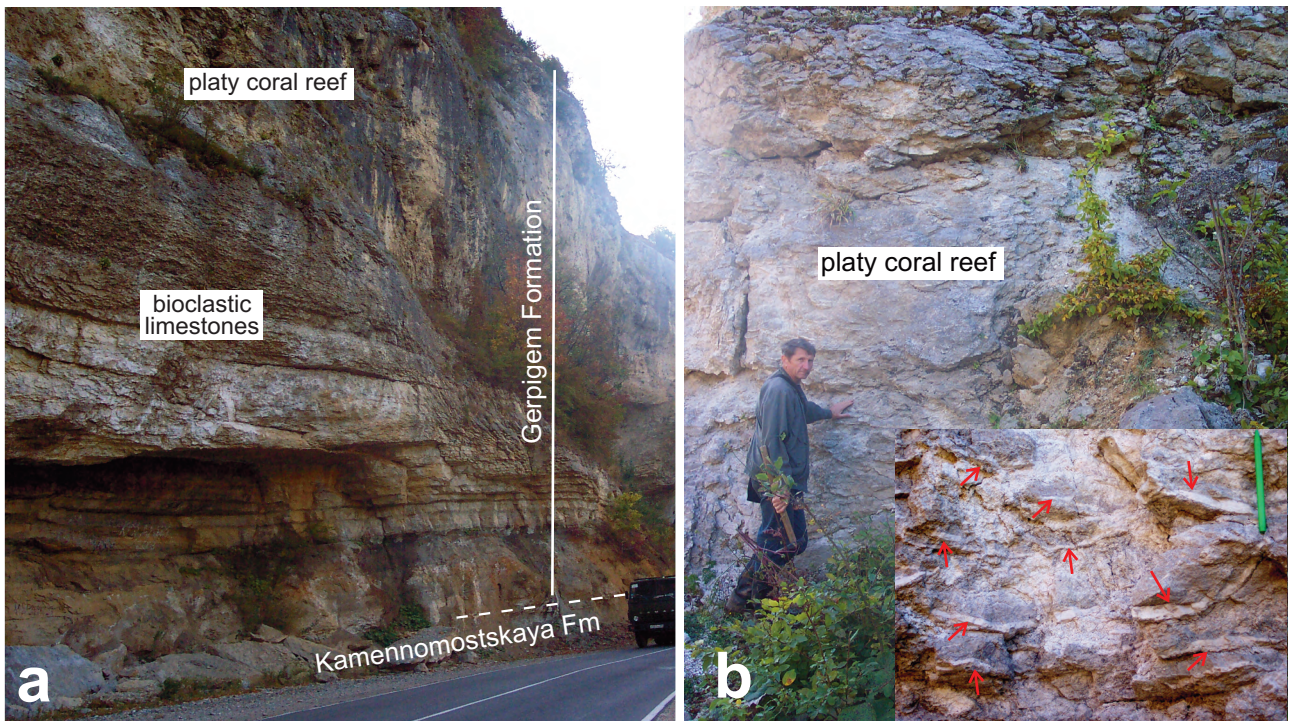
**Figure 6.** Upper Jurassic slope deposits exposed along the Malaya Laba River (locality WC116). This is made up of thick-bedded, poorly-sorted, micrite matrix-supported subangular limestone blocks, dominated by reefal debris.

Formation. It comprises mudstones interbedded with thin-medium-bedded bioclastic limestones, with abundant coral and sponge fragments, and plentiful bivalves. These grade upwards into massive reef facies that consist of coral-sponge rudstones in the lower part and platy coral reef limestones in the upper part. However, the reefs do not show mound or domal morphologies, but comprise thick biostromes. The transition between this reef succession and overlying well-bedded limestones and mudstones of

the Mezmayaskaya Formation crops out farther north along the Belaya River (locality WC58). The bedded carbonates consist of lagoonal bioclastic and micritic limestones that grade upward into gastropod and oncoidal limestones. Lagoonal mudstones were also examined at locality WC56.

#### *Lagonakskaya Zone*

*Overview*– In the Lago Naki region in the north-central part of the study area, Upper Jurassic rocks are assigned to the Lagonakskaya Formation or Group. The age of the formation has variously been determined as Oxfordian–Tithonian (Sidorenko 1968; Korsakov *et al.* 2002), Oxfordian–Early Tithonian (Khain & Lomize 1961) or Late Callovian–Tithonian (Ruban 2006; Afanasenkov *et al.* 2007). The formation is 850 m thick and is conformably overlain by at least 100 m of Berriasian oolitic and porcelaneous limestones of the Balki Sukhoy unit (Korsakov *et al.* 2002) (Figure 3). Its lower part (Upper Callovian–Oxfordian) is 200–250 m thick and comprises pale grey and massive coral reef limestones (Rostovtsev 1992). Within the Kimmeridgian–Tithonian part of the formation, two major NNW–SSE-trending reefs are developed in the Lago Naki plateau; the Oshtenski reef to the west and the Tsitsinskiy reef to the east (Rostovtsev 1992) (Figure 2). A third Guamskiy reef crops out at the northernmost edge of the Lago Naki



**Figure 7.** The Upper Jurassic succession exposed near the Belaya River (locality WC55). (a) Outcrop view of thin–medium-bedded bioclastic limestones with abundant coral and sponge fragments in the lower part and massive coral reef facies in the upper part. (b) Coral reef facies consisting mainly of platy coral boundstones. A close-up of the platy corals (arrowed) is shown in the insert.

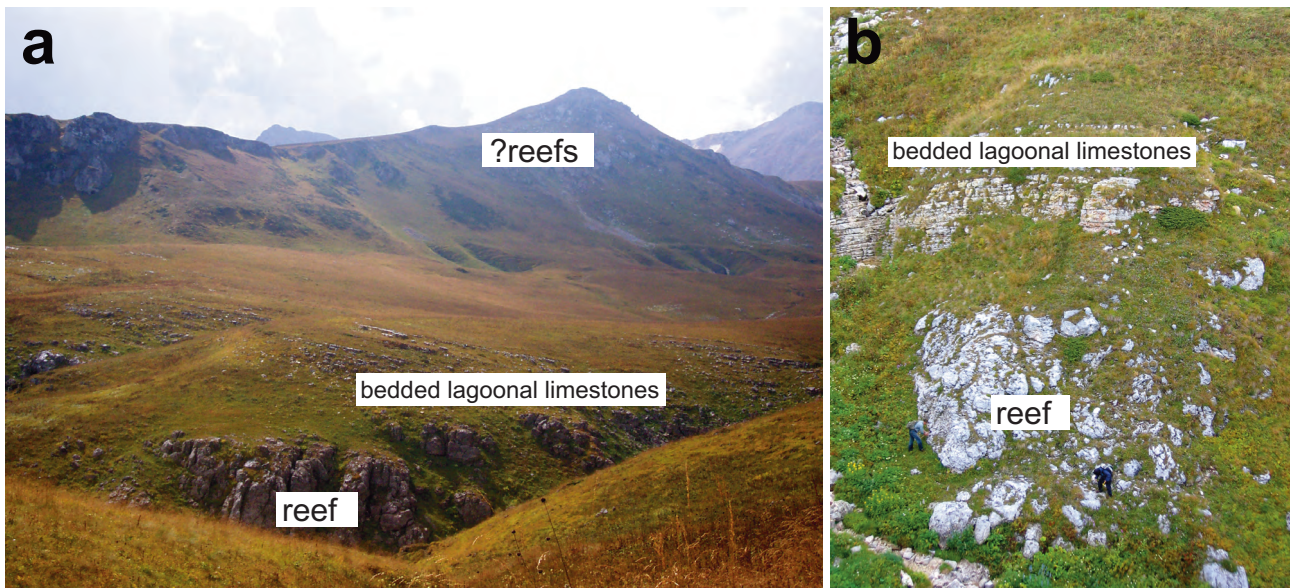
Plateau. A number of Russian studies suggested that the position of these Upper Jurassic reefs is fault controlled (Khain & Lomize 1961; Sedletskii *et al.* 1977; Boiko 1997). This would be consistent with their position at the margin of the fault-controlled Greater Caucasus Basin. Korsakov *et al.* (2002) mapped the Lakonakskaya Zone as having been thrust northward over the Labinskaya and Kuban zones (Figure 2), while earlier workers regarded the Upper Jurassic sediments of the Lago Naki region to be in lateral continuity with those of the Labinskaya Zone (Khain *et al.* 1971; Rostovtsev 1992).

*This Study*– Only the lower part of the Upper Jurassic succession was observed in this study (Figure 3). This consists of massive coral reef facies overlain by bedded back reef and lagoon facies (Figure 8). It is unclear what facies occur beneath the reef facies or how thick the reef unit is. The main reef-forming organisms are massive compound corals, which have variable sizes and growth forms. Reef framework

structures with growth cavities are commonly developed. Corals are encrusted by microbialites and microorganisms. Growth cavities are lined with early marine cements and occluded by blocky calcite. However, how the reef facies changed laterally and vertically, particularly towards the top of the section, is unclear because the rocks are poorly exposed and generally recrystallized. The massive reef facies are clearly overlain by bedded micritic and fenestral limestones that display subaerial exposure features, such as breccias and solution cracks associated with reddish sediments. Upwards, oncoidal limestones with foraminifera and lithoclasts are developed.

#### *Abino-Gunayskaya Zone*

*Overview*– In the Abino-Gunayskaya Zone, immediately to the west of the Lago Naki region, Oxfordian–Early Berriasian strata are called the Rezhetskaya Formation (Korsakov *et al.* 2002). The



**Figure 8.** The Upper Jurassic succession in the Lago Naki region (locality WC127). (a) The whole succession (the Lagonakskaya Formation) consists of at least two stages of reef development. This study examined the lower reef unit. This is overlain by bedded lagoonal limestones. (b) Detailed view of the transition between massive reef facies and bedded lagoonal limestones in the lower part of the Upper Jurassic succession.

formation is 600 m thick and consists mainly of slope deposits with detrital talus, gravity-flow-emplaced limestone blocks and interbedded marls and mudstones that increase in proportion westwards (Rostovtsev 1992). Kuznetsov (1993) also described the slope facies and observed complex sigmoidal-oblique clinofolds that grade into basinal turbidites that contain lithoclasts. Westwards, the Rezhetsyaka Formation passes into the laterally equivalent basinal Pshekhinskaya and Pikhtarskaya formations. The Oxfordian–Kimmeridgian Pshekhinskaya Formation is 230 m thick and disconformably (or ?unconformably) overlies Middle Callovian strata. It consists of mudstones and sandstones interbedded with lenses of detrital limestones (Korsakov *et al.* 2002). The Tithonian–Early Berriasian Pikhtarsyaka Formation is more than 530 m thick and conformably overlies the Pshekhinskaya Formation. It comprises intercalation of mudstones, marls, siltstones and sandstones with gravely limestone interbeds (Korsakov *et al.* 2002).

*This Study*– Upper Jurassic sediments were observed close to the Pshish River in the Abino-Gunayskaya Zone (localities WC34–WC36, WC158z

and WC158aa) (Figure 2). They form part of the Tithonian to Early Berriasian Pikhtarskaya Formation and comprise hemipelagic mudstones interbedded with varying amounts of calcareous very fine-grained to pebbly low-density turbidites deposited within a relatively deep basinal setting (Figure 9a).

#### *Nevebskaya Subzone*

*Overview*– In the core of the Russian western Caucasus, along the middle reach of the Tuapse River, thrust klippen contain the Oxfordian to Berriasian Gory Neveb Formation. The formation is over 1000 m thick and made up of detrital and micritic limestones, marls and rare mudstones. At its base, gravity flows containing limestone blocks of Oxfordian or older age along with sandy detrital limestones, mudstones and siltstones are developed (Korsakov *et al.* 2002).

*This Study*– Upper Jurassic strata are exposed at locality WC159 close to a working quarry and represent slope-basin facies. Rocks are faulted and folded, with massive proximal slope carbonate breccias tectonically juxtaposed against steeply

dipping, bedded more distal slope to basal deposits via a sub-vertical dextral shear zone (S. Rice, personal communication 2009). The proximal slope deposits consist of massive limestone breccias and megabreccias within a brownish marl matrix (Figure 9b). The poorly-sorted, chaotic breccias consist of lithoclasts exhibiting different microfacies types and transported fossils, and show a complex history of allochthonous sedimentation. The major textural types present in the breccias are lithoclastic and lithobioclastic rudstones, boundstones with corals and sponges, bioclastic floatstones and grainstones. Some coral-sponge boundstones are typical front-reef facies and consist of coral and sponge fragments and lithoclasts, which are well cemented by early marine cements (Figure 9c). Some breccias contain rounded limestone clasts, implying a degree of transportation, whilst others contain angular clasts that preserve delicate subaerial erosional fissures. Clearly, most clasts were derived from platform margin reefs and were transported downslope by gravity flow processes. More distal slope-basin deposits consist of thin- to medium-bedded calciturbidites interbedded with calcareous mudstones (Figure 9d).

#### *Chvezhipsinskaya Zone*

*Overview*– In the middle reaches of the Shakhe and Mzimta rivers on the southern side of the Russian western Caucasus, the Jurassic Aibginskaya and Ageptinskaya formations are recognised. The Callovian to possibly Tithonian Aibginskaya Formation is made up of 260 m of metre-scale interbeds of mudstone, siltstone and sandstone, along with thicker (~20 m) mudstone units; a basal conglomerate and sandy limestones may also be developed (Rostovtsev 1992; Lavrishchev *et al.* 2000; Korsakov *et al.* 2002). The Tithonian Ageptinskaya Formation is described as 150 m of micritic limestones and marls with brecciated limestones at its base (Lavrishchev *et al.* 2000).

*This Study*– Late Jurassic strata forming part of the Ageptinskaya Formation were observed at locality WC1f along the Mzimta River. The lower part of the succession is composed of a fine-grained peloidal-bioclastic grainstone-packstone and a coarse-grained shallow-water platform bioclastic packstone-rudstone with coral and crinoid fragments and

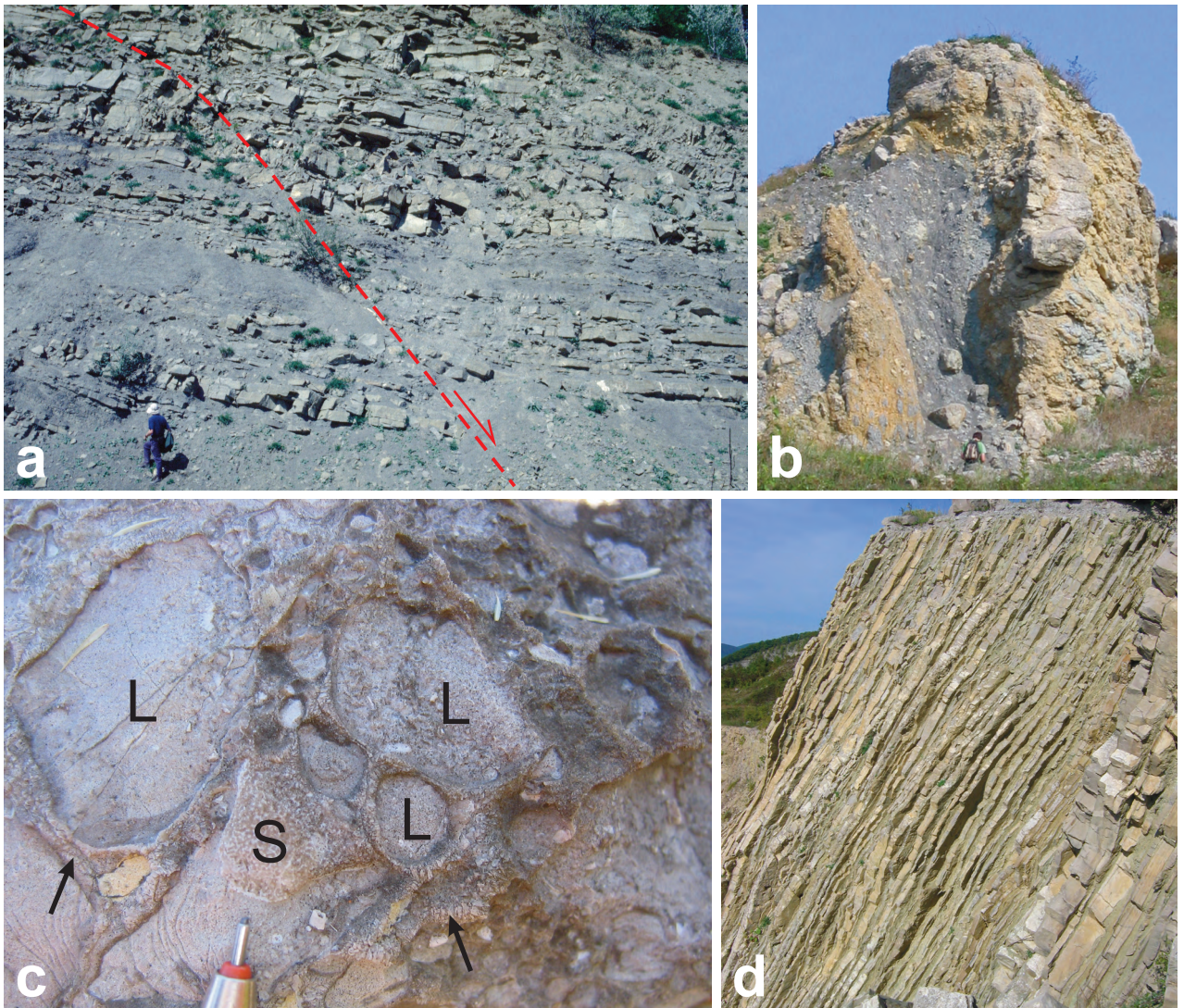
lithoclasts. This unit contains abundant reef debris, including coral, bryozoan and *Tubiphytes* fragments, together with microbialite clasts. The upper part of the succession consists of medium-bedded micritic limestones with chert nodules and thin-bedded argillaceous mudrocks. Possibly, the succession represents an upward transition from inner carbonate platform to outer platform-basin environments.

#### *Akhtsu Zone*

*Overview*– Possible middle Oxfordian to Tithonian sediments, known as the Katsirkhskaya Formation, crop out in the Akhtsu Zone on the southern side of the Russian western Caucasus. Basal conglomerates and sandstones show a great variation in lateral thickness, ranging from 4–5 m to over 100 m. They are overlain by 150–400 m of massive reef limestones that form part of the Akhtsu-Katsirkhi (Rostovtsev 1992) or Akhtsu-Abkhazia (Afanasenkov *et al.* 2005) barrier reef zone.

*This Study*– Upper Jurassic strata in the Akhtsu Zone were examined in a faulted anticline along the Mzimta River valley, south of locality WC1f (localities WC6a–e) (Figure 10a). They consist of shallow-water platform carbonates with well-developed reef facies. These were largely examined in fallen blocks as the facies were difficult to identify at road level because of poor exposure. The principal reef organisms are corals and calcisponges (Figure 10b). Growth cavities are also present. Branching corals were not observed. In comparison with other localities, it would seem that the reef facies contain more coral and sponge fragments and reworked reef debris (i.e. rudstones).

In the middle part of the succession, the facies consist of lithoclastic and bioclastic grainstones in the southern flank of the anticline and bioclastic packstones with sponges and coral fragments in the northern flank. The upper part of the succession on the southern flank of the anticline consists of intertidal-supratidal bioclastic limestones, abundant fenestral grainstone-packstones and algal packstones (localities WC6d, e). Breccias with red sediments occur as loose blocks along the road; these may have been derived from immediately beneath the unconformity mapped to occur at the top of the carbonate succession (Figure 3).



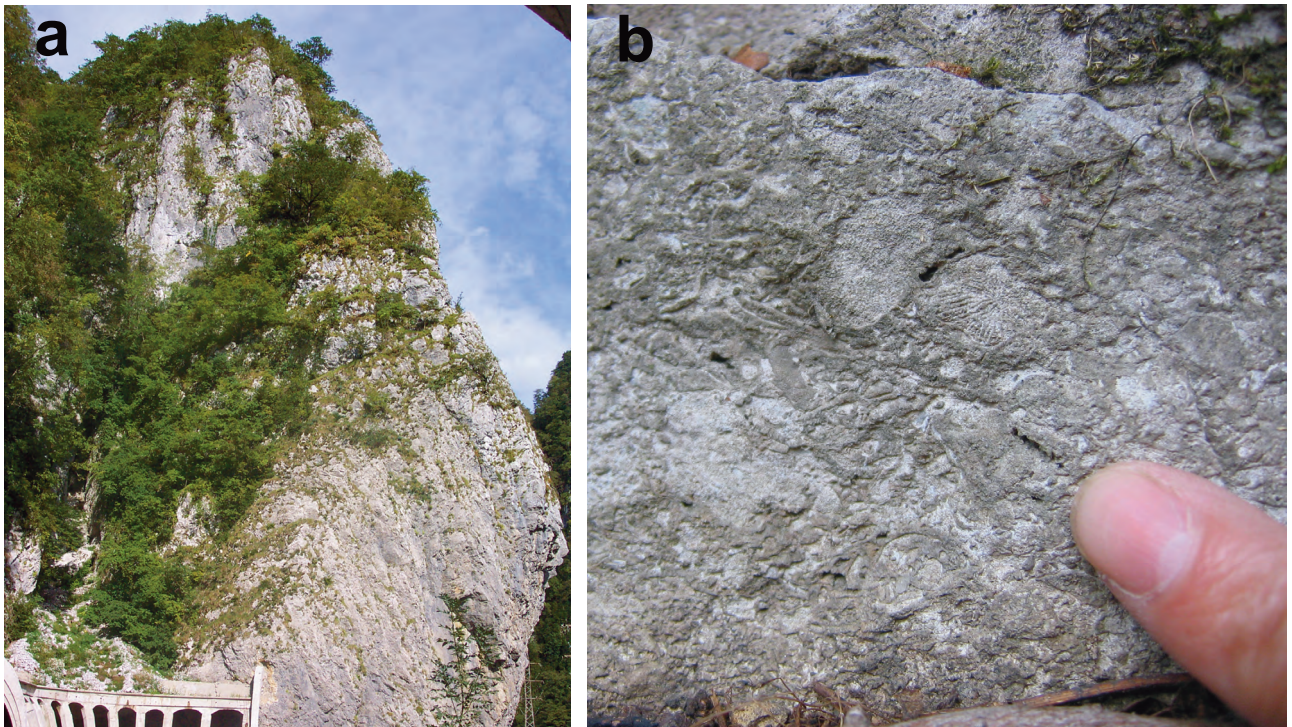
**Figure 9.** Upper Jurassic basinal and slope deposits in the Russian western Caucasus. (a) Interbedded mudstones and decimetre-bedded tabular turbidite sandstones of the Tithonian–Berriasian Pikhtarskaya Formation at locality WC35. The outcrop is cut by a normal fault. (b) Tectonically modified debris flow deposits (megabreccias) containing shallow-water limestone clasts up to several metres in diameter. (c) Poorly sorted lithoclastic rudstone with a calcareous sponge fragment (S) and lithoclasts (L) and abundant early marine cements (arrows). (d) Centimetre- to decimetre-bedded tabular calciturbidites and interbedded calcareous mudstones. Images b–d are from the Oxfordian to Berriasian Gory Neveb Formation at locality WC159.

### Reef Facies

The reefs encountered in this study tend to be either domal or massive. Domal reefs are tens of metres in size and were observed near the Bolyshaya Laba River at localities WC114 and WC115 (Figures 4 & 5). Massive reefs vary in thickness and can be more than one hundred metres thick. They were examined along the Mzimta River (locality WC6), near the

Belaya River (locality WC55), and in the Lago Naki region (WC127) (Figures 7, 8 & 10). However, the full extent of the massive reefs cannot be ascertained because of limited exposure.

The Upper Jurassic reefs observed in this study, like those formed along other parts of the northern margin of Tethys, can be grouped into three broad compositional types: (1) coral-dominated, (2)



**Figure 10.** Upper Jurassic reefs exposed as steep cliffs along the Mzimba River gorge (localities WC6a–e). (a) A general view of the Upper Jurassic reefs. (b) A loose block displaying coral-calcisponge reef limestone facies.

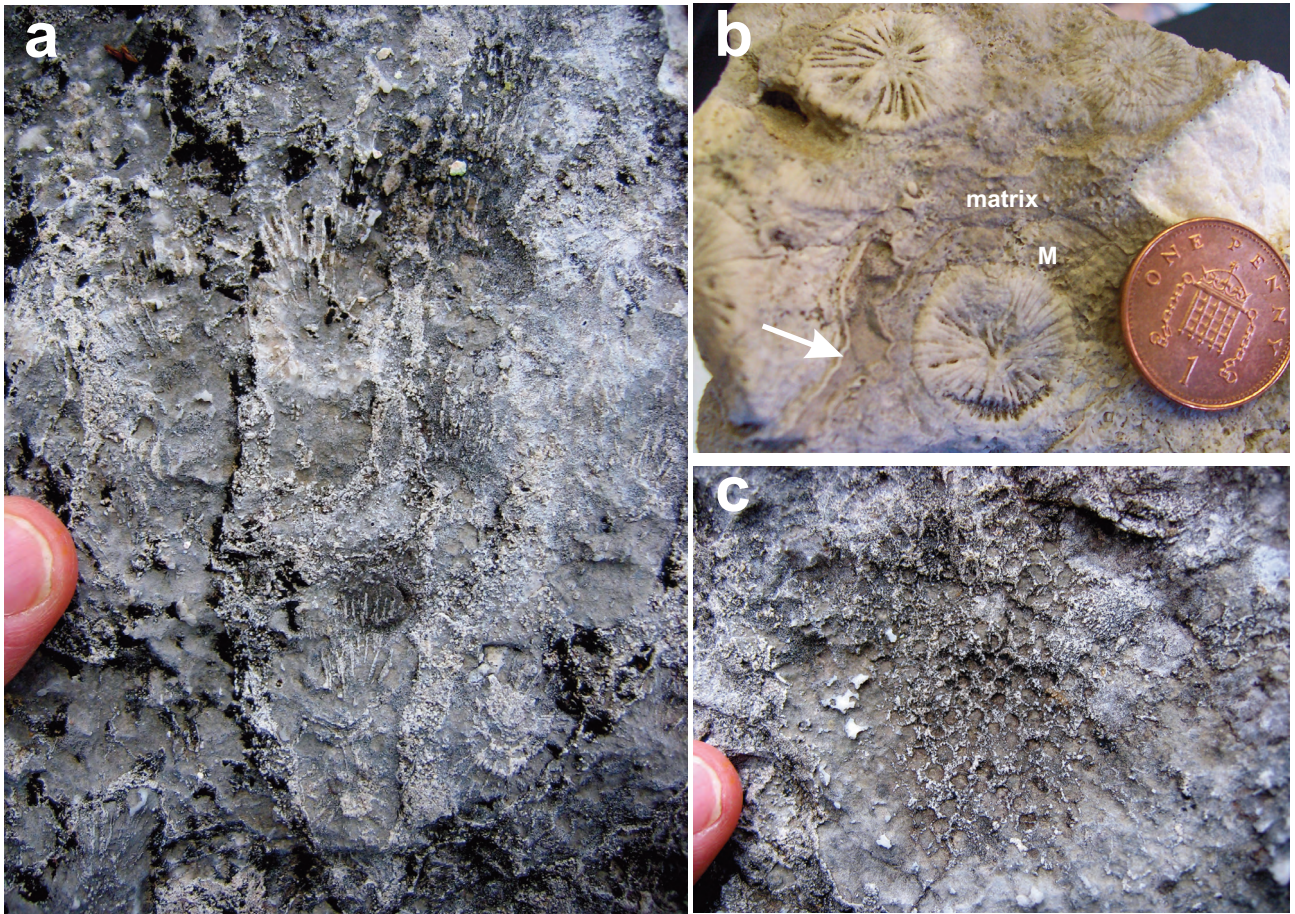
siliceous sponge-dominated; and (3) microbialite-dominated (Leinfelder *et al.* 1996, 2002). These are described in more detail below. Each type of reef reflects different bioconstructions and depositional environments.

#### *Coral-dominated Reefs*

The coral-dominated reefs can be further divided into (1) higher-diversity coral and (2) low-diversity platy coral types.

*Higher-diversity Coral Reefs*– Higher-diversity coral reefs have either domal (locality WC115) or massive (localities WC6 and WC127) aspects. They are composed of coral reef boundstones, together with coral rudstones and floatstones. It was difficult to assess the full distribution of facies within these reef bodies because exposures are often in steep, inaccessible cliff faces. Corals show a medium to high generic diversity and different growth morphologies (Figures 11 & 12). The major coral types recognised include *Calamophylliopsis*, *Cyathophora*, *Dermoseris*,

*Isastraea*, *Montlivaltia* (Montlivaltiidae), *Stylina* (Stylinidae), *Stylosmilia*, *Thammasteria*, *Thecosmilia* and platy Microsolenidae. Corals are also associated with a small proportion of other macro-faunal elements, such as bryozoans and calcisponges, together with brachiopods and bivalves, which contribute in varying degrees to the reef framework. Corals show variable morphologies, sizes and abundance from locality to locality and generally constitute 20–50% of the total rock volume. Laminar or sheet-like corals have been commonly found in the lower part of the reef succession at locality WC115. Massive and branching corals occur at locality WC127. Corals acted as the main component of vertical reef growth and provided the skeletons on which abundant microorganisms and microbialites were encrusted (Figure 13). The encrusting microorganisms (mainly microproblematica) are identified as *Bacinella-Lithocodium*, *Iberopora*, *Koskinobullina*, *Prismenproblematikum*, *Tubiphytes* and serpulids, and are heterogeneously distributed. Microbialites are commonly encrusted on the

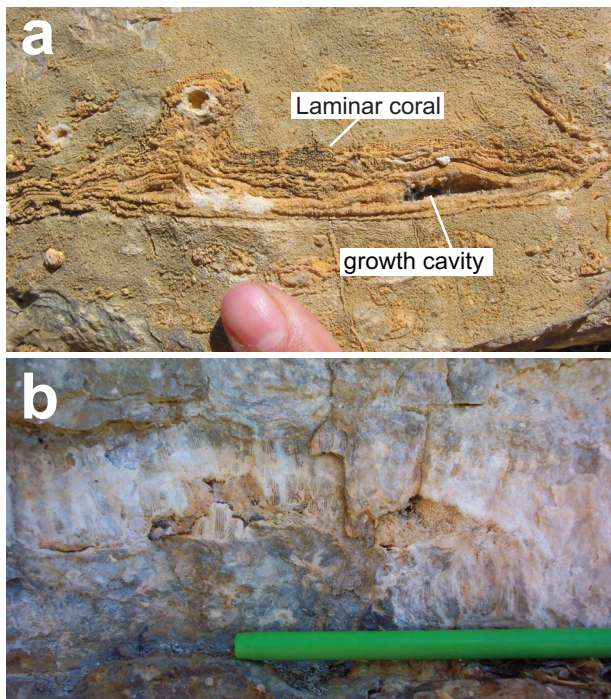


**Figure 11.** Taxonomical differences in compound corals in Upper Jurassic reef facies from the Lago Naki region (locality WC127). (a) An oblique section through branching corals. (b) A transverse section through branching coral colonies. Note that the reef framework consists of corals that are encrusted by microbes and microbial fabrics (M). A n arrow indicates a growth cavity. (c) Small coral colonies.

microorganisms and exhibit clotted and peloidal structures. Sometimes microbialites show lamination that can be up to a few centimetres in thickness. In some places, microbialites directly overgrew corals. Inter-skeletal spaces within the coral reef facies are commonly filled with a bioclastic wackestone or packstone matrix that usually contains crinoid and brachiopod fragments. In some places, such as at locality WC127, bioclastic grainstones have been observed in the reef matrix. Growth cavities are commonly developed and filled with early marine isopachous fibrous cement and occluded by blocky calcite cement. At locality WC115, some growth cavities have remained partially open (Figure 12a).

*Low-diversity Platy Coral Reefs*– A low-diversity platy coral reef has been observed near the Belaya

River at locality WC55. This reef has a massive aspect and is developed on a ~10-m-thick coral debris and bioclastic limestone unit (Figure 7a). The reef is approximately 10 m thick and is characterised by a coral community with low generic diversity dominated by frame-building platy corals (microsolenids). The platy corals vary slightly in form and dimensions and are commonly 1–2 cm in width and several to tens of centimetres in length (Figure 7b). Their elongate plates are commonly parallel to each other. The reef facies are largely neomorphosed and partially dolomitized. Diagenetic overprints have obscured original textures, such as the encrusting features and matrix (Figure 14). Locally, a bioclastic wackestone matrix with skeletal fragments of corals and bivalves has been identified. There are abundant



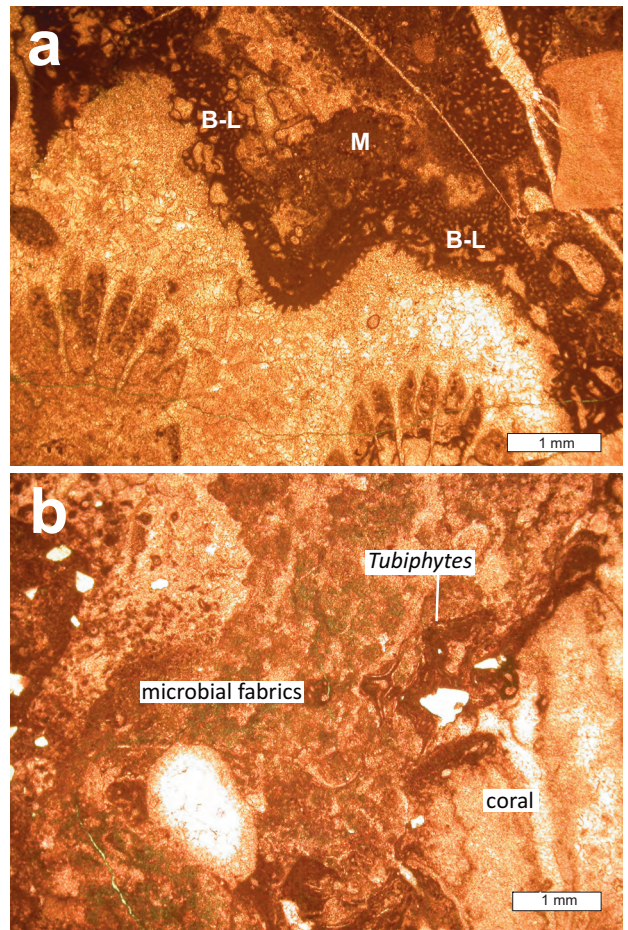
**Figure 12.** Upper Jurassic coral-dominated reef facies at locality WC115, Bolyshaya Laba River. (a) Reef facies containing laminar corals and a growth cavity that is only partially filled with early marine cements. (b) A large laminar compound coral.

cavities in the facies, including mouldic and solution pores.

### *Siliceous Sponge-dominated Reefs*

Siliceous sponge-dominated reef facies, associated with microbialite-dominated reef facies, are exposed near the Bolyshaya Laba River at locality WC114 in a large composite mound complex with a thickness of approximately 5–30 m and a lateral extent of 50 m. The mound complex is composed of small individual, more or less coalescent tabular to lenticular bodies. However, it is difficult to distinguish the siliceous sponge-dominated reef facies from microbialite-dominated reef facies in the field due to intense weathering. The size of individual bodies is also uncertain.

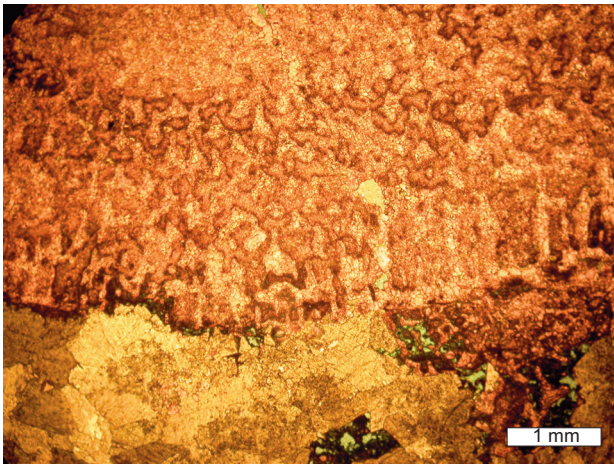
The siliceous sponge-dominated reef facies are mainly composed of siliceous sponges, together with microbialites and a small amount of encrusting microbes. They display a rubble-like or nodular appearance in the field. In thin section, some siliceous



**Figure 13.** Thin-section photographs of coral reef structures. (a) Corals encrusted mainly by *Bacinella-Lithocodium* (B-L) and microbial fabrics (M), Akhtsu, (locality WC6b). (b) *Tubiphytes* and microbial fabrics overgrown corals, Lago Naki (locality WC127).

sponge skeletons with rayed spicules are preserved (Figure 15a). However, the original siliceous skeletons are largely replaced by sparry calcite, although in some spicules silica still remains. The spaces between the spicules are filled with micrite and peloids. In some places, the original siliceous skeletons are completely replaced by calcite producing a 'pseudopelletoid fabric' (see Brunton & Dixon 1994), but the gross outer shape of the sponges are preserved (Figure 15b). The siliceous sponges are commonly overgrown by microbialites that appear as dense or peloidal domal or irregular patches with various thicknesses. Both siliceous sponges and microbialites are locally colonised by the agglutinating worm tube *Terebella* and foraminifera (nubeculariid).





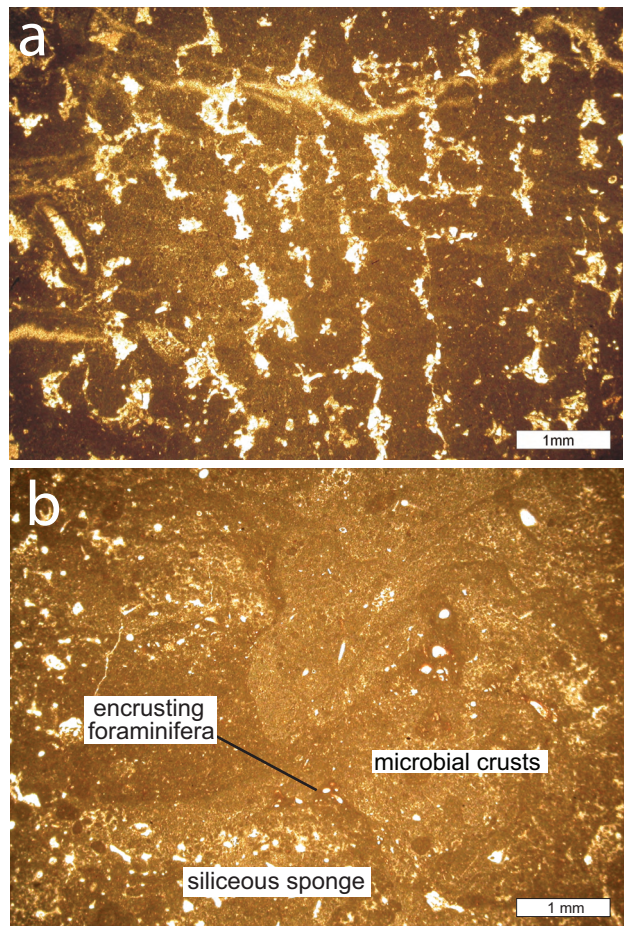
**Figure 14.** Thin-section photograph showing a partially dolomitized platy coral boundstone, Belaya River (locality WC55).

#### *Microbialite-dominated Reefs*

Microbialite-dominated reef facies occur as patchy, lenticular or small bioherms associated with siliceous sponge reef facies at locality WC114 (Figure 16). They appear to become more prominent towards the top of this succession. In some places, they display columnar-branching thrombolitic-stromatolitic structures with a thickness of 20 cm (Figure 16a). In thin section, microbialites display a variety of growth forms, such as branching, columnar, domical or conical masses. They have a dense micritic to peloidal composition, and appear to be either crudely laminated (stromatolite) or clotted (thrombolite) (Figure 16b–d). The microbial lamination consists of alternating light and dark laminae. The light laminae comprise small peloids and the dark laminae are composed of micrite. They are frequently encrusted by nubeculariid foraminifera and small annelid tubes. The matrix between microbialites is dense micrite with scarce fossils. Boring structures occur in the facies.

#### **Reef Growth and Depositional Environments**

Most reefs are developed during sea-level rise and early highstand (e.g., Sarg 1988; Tucker & Wright 1990; Leinfelder 1993a; Insalaco *et al.* 1997; Nose & Leinfelder 1997; Tucker 2003). However, the type of reef to grow is dependent on localized environmental conditions. The main controlling factors on reef

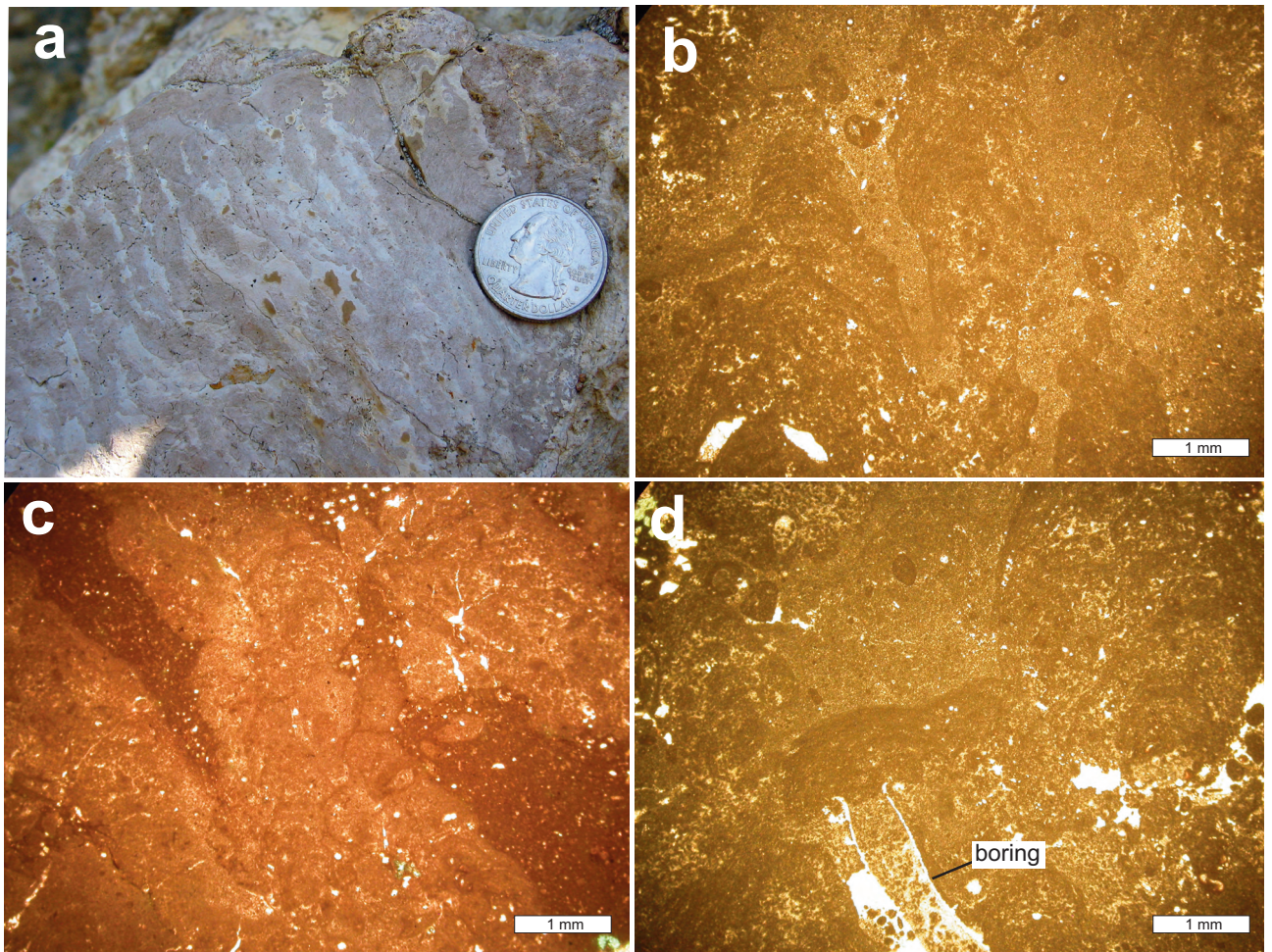


**Figure 15.** Thin-section photographs of the siliceous sponge and microbialite reef facies, Bolyshaya Laba River (locality WC114). (a) A siliceous sponge showing rayed spicules that have been dissolved and partially replaced by sparry calcite. (b) A siliceous sponge overgrown by foraminifera and microbial crusts.

growth are water depth (light intensity), energy levels, sedimentation rate, temperature, suitable substrate availability, oxygenation and circulation, salinity and nutrients (Fagerstrom 1987). The palaeoenvironment of each reef type is discussed in the following sections.

#### *Higher-diversity Coral Reefs*

Higher-diversity coral reefs have been documented from Upper Jurassic successions in many places along the northern margin of Tethys (see Insalaco *et al.* 1997). They have been generally regarded to form in shallow-water conditions with normal salinity, warm waters and good illumination (Leinfelder *et al.*

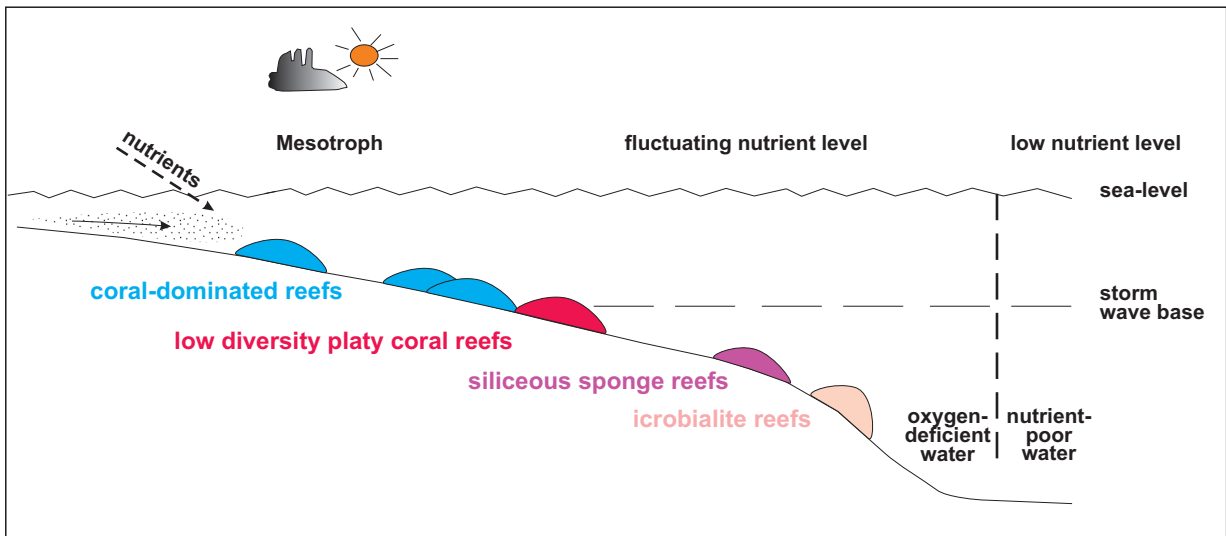


**Figure 16.** Microbialite-dominated reef facies, Bolyshaya Laba River (locality WC114). (a) Branching, columnar microbialites in the field. (b-d) Thin-section photographs showing the details of the columnar crude stromatolitic (b) and thrombolitic (c, d) microbialites.

1996, 2002) (Figure 17). Colonial corals commonly grew in shallower, turbulent waters, out competing other organisms (Leinfelder & Schmid 2000). However, different coral growth forms may reflect environmental variations (Leinfelder *et al.* 2002). For instance, branching corals thrived in relatively lower energy platform interiors, whereas massive corals were more prevalent at platform margins. Associated reefal encrusters are also environmentally sensitive and symptomatic of low sedimentation rates (Leinfelder 1993b). *Bacinella-Lithocodium* encrusters were strongly light-dependant and occurred in relatively clear and shallow-water environments (Schmid 1996; Dupraz & Strasser 1999; Flügel 2004).

Abundant *Tubiphytes* may indicate deeper-water conditions such as in a mid ramp environment (Schmid 1996).

The higher-diversity coral reefs observed in this study were likely formed in shallow-water siliciclastic sediment-free environments during relative sea-level rise, an interpretation supported by the presence of a number of shallow-water dependant micro-encrusting organisms. The occurrence of *Tubiphytes* is limited in this study. The reefs were initially generated by laminar or sheet-like corals and other framework builders that attached themselves to hard-substrate at bathymetric highs. Then, the corals spread rapidly over the surrounding unconsolidated sediments,



**Figure 17.** Schematic diagram showing the major control factors on the growth and distribution of Upper Jurassic reefs on a carbonate platform (modified from Leinfelder *et al.* 2002).

providing substrates for the growth of encrusting organisms and microbialites. These encrusters played an important binding role and also contributed calcium carbonate to the reef framework. Corals in the Lago Naki region (locality WC127) were densely colonised and are dominated by massive growth forms, although both massive and branching types are present. The energy conditions of the higher-diversity coral reefs in the study area varied through time and also from locality to locality. The presence of a grainstone matrix in some reef facies in the Lago Naki region (locality WC127) suggests high-energy conditions prevailed here (see Insalaco *et al.* 1997).

#### *Low-diversity Platy Coral Reef*

Platy (microsolenid) coral reefs were a very common reef type in the Late Jurassic. They usually contain a large amount of siliciclastic material (Insalaco 1996) and lack binding microbialites (Leinfelder *et al.* 1996). They commonly occur as biostromes due to their platy growth habit, which did not allow them to establish a pronounced relief (Insalaco 1996). The growth form of microsolenids can be compared with that of the present-day coral *Leptoseria fragilis*, which is found only in deep water (90–130 m) in the Gulf of Aqaba near Eilat, Israel (Insalaco 1996). The flat platy shape has been suggested to be the most efficient

growth form for a coral to catch all the available light in deeper-water environments (Leinfelder *et al.* 1996). As a result, microsolenid coral reefs of Late Jurassic age have been interpreted to form in mid to outer ramp deeper-water environments under low light intensities, low energy levels, low sedimentation rates and high nutrient levels (Insalaco 1996; Leinfelder *et al.* 1996) (Figure 17).

The low-diversity platy coral reef observed in this study does not contain siliciclastic material. Low-diversity platy coral reefs without siliciclastic sediments have also been reported from Upper Jurassic rocks and are suggested to have formed in similar settings as those with siliciclastic sediments (see Insalaco 1996; Insalaco *et al.* 1997). Unfortunately, the low-diversity platy coral reef observed in this study is strongly altered by both recrystallization and dolomitization, such that it is difficult to know what types of micro-encrusters and matrix are present in order to provide further evidence for the environment of growth.

#### *Siliceous Sponge-dominated Reefs*

Upper Jurassic siliceous sponge-dominated reefs have been widely reported from southern Germany, the Swiss and French Jura, Poland, North America

and Portugal (Gwinner 1976; Bernier & Gaillard 1980; Baria *et al.* 1982; Trammer 1982, 1989; Crevello & Harris 1984; Koch & Schorr 1986; Ellis *et al.* 1990; Pisera 1991; Schmid 1996). Many of them have been suggested to grow in deeper-water environments with water depths estimated as 50–60 m (Reitner & Neuweiler 1995), 70 m (Leinfelder *et al.* 1993b) and exceeding 150 m (Gwinner 1976). It is possible that the depositional depths of the siliceous sponge-microbialite reefs in the Late Jurassic could be even deeper based on the modern siliceous sponge reefs that occur in water depths of 165–240 m on the continental shelf off British Columbia, Canada (see Krautter *et al.* 2006) (Figure 17). According to Krautter *et al.* (2006), the modern siliceous sponge reef framework is established by sponges using the macerated skeletons of dead sponges for (1) laval settlement sites, (2) providing stabilizing supports during growth and (3) forming elaborate and close intergrowths. The ability of modern siliceous sponges to trap or create sediment mounds indicates low sedimentation rates and very low wave energy. Siliceous sponges thrived and colonized the sea floor during Late Jurassic time, acting as bafflers, binders or/and even contributors to reef frameworks (Brunton & Dixon 1994). They also enabled encrusting foraminifera and the worm tube *Terebella* to colonize, and especially abundant microbialites to grow (Leinfelder *et al.* 1996; Dupraz & Strasser 1999, 2002). Microbialite encrustation provided a crucial role in stabilizing the reef framework. The occurrence of abundant microbialites is also indicative of low sedimentation rates and quiet water conditions generally below storm-wave base (Leinfelder *et al.* 2002).

#### *Microbialite-dominated Reefs*

Microbialites occur widely in Upper Jurassic reef facies. They can be conspicuous in coral-dominated reefs, appear prominent in siliceous sponge-dominated reefs and are dominant where other reef builders are scarce (Riding 2002). According to Riding (2002), microbialite formation involves two contrasting processes: (1) microbially mediated precipitation on or within extracellular polymeric substances; and/or (2) microbial films trapping and stabilizing loose sediment. Water energy, depth

and sedimentary rates are the important factors controlling microbialite growth (Braga *et al.* 1995; Schmid 1996).

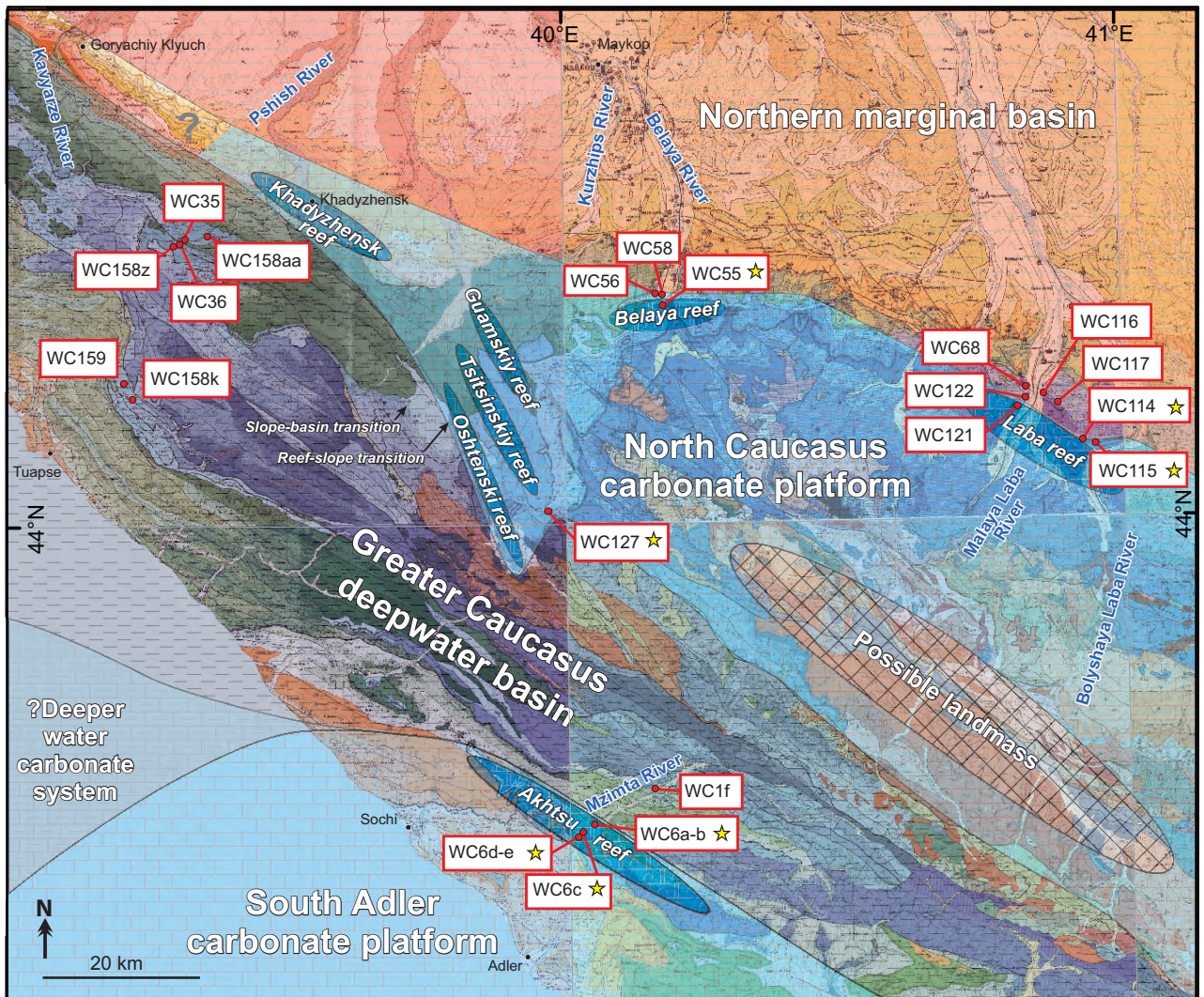
Upper Jurassic microbialite-dominated reefs have been interpreted to form in low energy and deep-water settings such as outer ramps under very slow sedimentary rates (Leinfelder *et al.* 1996; Schmid 1996) (Figure 17). Most widespread microbialites occurred in normal marine settings of greater than 70 m water depth and as deep as 400 m (e.g., Keupp *et al.* 1993; Leinfelder 1993a; Dromart *et al.* 1994; Rehfeldt 1996; Schmid 1996; Mancini *et al.* 2004). The occurrence of scarce fauna in the microbialite-dominated reefs observed in this study suggests a deep-water setting where many other reef metazoans could not survive due to partial oxygen depletion (see Leinfelder *et al.* 2002). In a low hydraulic energy anaerobic environment, the microbialite growth reflects an irregular and uneven supply of sediments on surfaces that were patchy colonized by various sciaphile bacteria (Camoin *et al.* 1999). The different growth forms of stromatolitic lamination and thrombolite clotting reflect either even or uneven episodic accretion, respectively (Braga *et al.* 1995).

#### **Regional Facies Distribution**

Two carbonate platforms have been recognised in the Russian western Caucasus; an unnamed platform to the north and the South Adler platform to the south (Rostovtsev 1992; Afanasenkov *et al.* 2005; Panov 2006). These occur on either side of the Greater Caucasus Basin (Figure 18). Reef occurrences at localities WC114 and WC115 on the Bolyshaya Laba River, locality WC55 on the Belaya River and locality WC127 in the Lago Naki region are developed on the former platform, which is named here the north Caucasus platform, whilst the reefs at locality WC6a–e on the Mzimta River are developed at the northern margin of the latter platform.

Most reefs observed in this study occur in the lower part of the Upper Jurassic succession and are presumed to be of Oxfordian age (Figure 3). Reef growth, however, continued into Tithonian times in the Akhtsu and Lagonakskaya zones.

At locality WC115, the higher-density coral reef observed in the lower part of the Upper Jurassic



**Figure 18.** Distribution of Upper Jurassic carbonate platform and associated facies in the Russian western Caucasus including known reef localities. Note that the palaeoenvironment map is constructed on a present day base map with no account made for the effects of tectonics.

succession was likely to have been developed in a shallow-water, higher-energy ramp setting. This grades into siliceous sponge-microbialite and microbialite-dominated reefs towards the northwest (locality WC114) where deeper-water, lower-mid to outer shelf conditions were developed. Farther towards the northwest at locality WC116, slope deposits contain abundant reef debris, including various lithoclastic rudstones and floatstones. A similar facies trend from platform carbonates with reefs to slope deposits is also developed northward between localities WC121 and WC122. These indicate

that a north-facing carbonate platform graded into slope and possibly marginal basin environments at the northern limit of Upper Jurassic exposure in the Labinskaya Zone (Figure 18). The existence of a marginal basin is indicated by the occurrence of thick Kimmeridgian to Tithonian evaporates north of the Caucasus (Baikov 2004).

Reefs at the Belaya River section (locality WC55) are represented by a low-diversity platy coral type that was probably formed in a mid ramp setting. There is no outcrop evidence to determine the orientation of this ramp although, as a continuation of the ramp

exposed along the Laba River, this is also likely to have faced north (Figure 18).

Thick and massive coral reefs are present in the Lago Naki Plateau. These are regarded to be barrier reefs that formed along the southwestern margin of the north Caucasus platform (Sedletskii *et al.* 1977; Kuznetsov 1993; Baikov 2004). Non-deposition or erosion means that there is no evidence for a continuation of this barrier reef belt to the southeast of the Lago Naki region. However, subsurface data presented in Afanasev *et al.* (2007) from the Khadyzhensk region, does suggest that at least discontinuous southwest-facing reefs occur farther to the northwest along the same northwest-southwest trend as the Oshtenski and Tsitsinskiy reefs mapped in the Lago Naki region by Korsakov *et al.* (2002) (Figure 18). Afanasev *et al.* (2005) postulated that this reef system, which they named the Khadyzhensk reef belt, continued along the northeastern margin of the Greater Caucasus Basin to the Taman Peninsula.

The massive coral reef facies observed at locality WC127 in the Lago Naki region (of probably Oxfordian age) are overlain by bedded shallow-water lagoonal facies. This might suggest that the reef succession was interrupted by a drop in relative sea level. It is possible that this was time equivalent to that responsible for the major erosion surface identified at locality WC115 on the Bolyshaya Laba River. Presumably, as sea-level rose again, the upper reef sequence formed.

West of the Lago Naki reef belt, Upper Jurassic slope facies (the Rezhetskaya Formation) can be traced towards the northwest over a distance of 10 km into basinal facies (the Pshekhinskaya and Pikhtarsyaka formations) within the northern part of the Greater Caucasus Basin (the Abino-Gunayskaya Zone; Figure 2) (Kuznetsov 1993; Korsakov *et al.* 2002). The approximate position of this shelf-slope break is marked by the Navaginskaya Fault (Figure 2). This might suggest that it marks the position of an earlier structural discontinuity.

The presence of distinctive slope depositional systems with proximal and distal slope facies associations at locality WC159 within the Greater Caucasus Basin is intriguing. Either these form part of the tectonically-dismembered reef-slope-basinal transition described above or they form the remnant of another reef-slope system not exposed at outcrop.

Massive shallow-water carbonate facies at locality WC6 in the Mzimta River valley form part of the Akhtsu-Abkhazia reef belt at the northern margin of the South Adler carbonate platform (Afanasev *et al.* 2005) (Figure 18). *In situ* reef framework structures have not been seen, but are common as clasts in rudstones. The presence of abundant coral and other reef debris suggests a higher-energy, shallow-water shelf setting. These reef facies are associated with back-reef facies, such as bioclastic rudstones-grainstones and bioclastic packstones. They are overlain by very shallow-water lagoonal facies, such as fenestral limestones, bioclastic-peloidal grainstones and cyanobacterial grainstones-packstones at the top of the succession.

Evidence for the north-facing nature of the Akhtsu-Abkhazia reef belt comes in the form of a deepening-up succession observed at locality WC1f, northeast of locality WC6 (Figures 2 & 18). These are interpreted to represent a transition from inner carbonate platform to outer platform-basin environments and are likely to be transitional into age-equivalent basinal flyschoid deposits mapped farther north in the Novorossiysko-Lazarevskaya Zone of the Greater Caucasus Basin (Rostovtsev 1992).

According to Afanasev *et al.* (2005), the Akhtsu-Abkhazia reef belt trends offshore in the vicinity of Sochi fringing the South Adler carbonate across the middle part of the Shatskiy Ridge in the eastern Black Sea (Figure 18). This platform continues onshore in the Rioni Basin region of West Georgia, with fringing reefs again occurring to its the north (Bendukidze 1978; Adamia *et al.* 1992).

## Conclusions

The Upper Jurassic reefs in the Russian western Caucasus are similar to those formed along other parts of the northern margin of Tethys. They can be grouped into coral-dominated, siliceous sponge-microbialite and microbialite types. Each reef type has a different bioconstruction and reflects deposition under different environmental conditions.

Coral-dominated reefs occur as patchy, thick biostromal and massive forms, and have a wide distribution in shallow-water shelf settings. Higher-

diversity coral reefs were formed either at shallow-water platform margins or in platform interiors. Low-diversity platy coral reefs occurred in deeper-water, mid shelf settings. Siliceous sponge-microbialite and microbialite reefs occur as lenses (bioherms) and mounds and were restricted to deeper-water mid-outer shelf environments.

The Upper Jurassic reefs exposed in the Russian western Caucasus are potential analogues for Upper Jurassic reefs in the subsurface of the eastern Black Sea. If the Akhtsu-Abkhazia reef belt extends into the eastern Black Sea as suggested by Afanasenkov *et al.* (2005) (see Figure 18), reefs formed along the South Adler carbonate platform margin could be analogous to the reef succession exposed at locality WC6 in the Mzimta valley. This is dominated by higher-density coral reefs formed in higher-energy conditions with abundant reef debris.

Numerous possible isolated reef complexes have been identified from the northern Shatskiy Ridge during Russian seismic surveys (Afanasenkov *et al.* 2005) (Figure 1). There are no data on the type or depositional environment of these reefs, although it is generally assumed that they were deposited in deeper-water settings (see Afanasenkov *et al.*

2005). If so, it is likely that siliceous sponges and microbialites would form major contributors to reef growth, with these reefs being comparable with those present at locality WC114. Alternatively, if the reefs had developed in shallower water, higher diversity coral-dominated reefs are likely to have been the main reef type. These would be comparable with those examined at a number of localities in this study, such as at WC6, WC55, WC115 and WC127.

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