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# Coesite in the eclogite and schist of the Atantayi Valley, southwestern Tianshan, China

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Coesite is an indicator mineral of ultra-high-pressure metamorphism. Since coesite was reported in the Habutengsu Valley, we have also found it in eclogite and schist from the Atantayi Valley in the southwestern Tianshan, China. Petrographic and micro-Raman analyses were carried out for the Atantayi metamorphic rocks and coesite was recognized in the predominant rock types, i.e. schist and eclogite, from three sections. The coesite-bearing schist consists mainly of garnet, Na-Ca amphibole, quartz, white mica and albite; the coesite-bearing eclogite is mainly composed of omphacite, garnet, glaucophane and zoisite. The coesite occurs as various mineral inclusions within porphyroblastic garnet. Findings of coesite in eclogite and associated schist indicate not only the regional *in situ* formation of the Atantayi ultra-high-pressure eclogite, but also the large areal extent of ultra-high-pressure metamorphism in southwestern Tianshan, extending up to 10 km north-south and 60–80 km east-west.

**southwestern Tianshan orogen, coesite inclusions, UHP metamorphism**

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Coesite is an indicator mineral of ultra-high-pressure (UHP) metamorphism [1]. In well-established UHP belts worldwide, coesite is usually preserved in relatively refractory minerals, such as garnet and zircon. An increasing number of studies show that garnet can preserve abundant information on the pressure-temperature (P-T) evolution of a metamorphic garnetiferous rock, as evidenced by the applicability and reliability of garnet isopleth geothermobarometry [2]. In the UHP field, the occurrence of coesite inclusions in garnet is of significance because it identifies the possible episodic growth of garnet, which may, combined with garnet isopleth thermobarometry, decipher the P-T trajectory of a specific UHP rock. The first reports of UHP metamorphism in the southwestern Tianshan instigated debate that has continued until the recent discovery of coeiste in the Habutengsu Valley of this orogenic belt [3–8]. However, until now, coesite had not been optically identified in the rocks of the Atantayi Valley, where the eclogites involved in the “UHP versus HP” controversy were sampled [5,9]. Detailed investigations of UHP minerals such as coesite are critical for elaborating on the spatial distribution and evolutionary characteristics of the UHP belt in the southwestern Tianshan. Recently, we collected a number of samples of different rock types along the Atantayi Valley and conducted detailed petrographic analyses on them. In order to find any evidence of ultra-high pressures in these rocks, we carefully examined tiny inclusions in garnets found in these samples employing Raman spectroscopy. This has provided fundamental information on the metamorphic evolution of the HP-UHP belt of the southwestern Tianshan.

## 1 Geological background

The HP-UHP belt located in the southwestern part of the Tianshan orogen of Central Asia is associated with the amalgamation of the Yili-Central Tianshan and Tarim plates,

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as a result of the north-directed subduction of the Paleo-Tianshan Ocean. This wedge-shaped metamorphic belt extends ENE-WSW for approximately 200 km in NW China (Figure 1(a)), with a maximum width of about 20 km [10,11]. To the north it is bounded by South Central Tianshan Fault, and to the south it has a tectonic contact with Early Paleozoic carbonate strata of low metamorphic grade. The HP-UHP belt of southwestern Tianshan consists of schist, eclogite, blueschist, marble and serpentinite. As the predominant rock type, the mineral modal content of the schists varies considerably from place to place and at least four representative types were recognized: pelitic, felsic, calcareous and mafic schists. Eclogite and blueschist largely occur in lens to massive block sizes (with 0.1 m to100 m

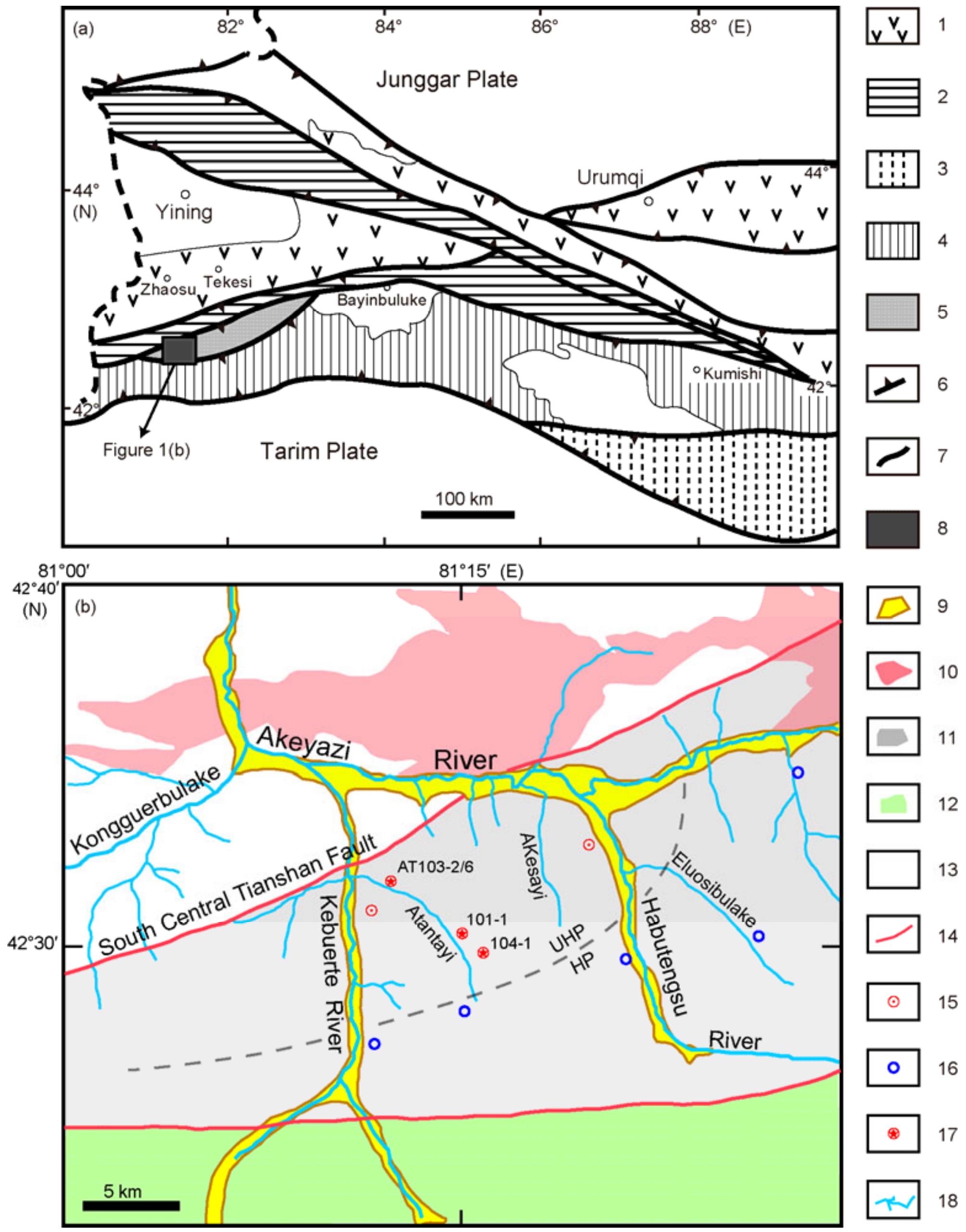


**Figure 1** Simplified geological maps of the orogenic belt of southwestern Tianshan (a) and the sample area (b) (modified after [11], 1)). 1, Late Paleozoic volcanic and volcaniclastic rocks; 2, Precambrian basement, Paleozoic granites and Paleozoic strata; 3, Precambrian amphibolite facies metamorphic rocks; 4, Paleozoic strata; 5, HP-UHP belt; 6, thrust; 7, fault; 8, study area; 9, Quaternary alluvial; 10, granitoid; 11, HP-UHP complex; 12, Marble; 13, Precambrian basement, Paleozoic strata and volcanics (undifferentiated); 14, fault; 15, UHP rock locality [3,4,12]; 16, blueschist locality; 17, sample locality; 18, river. Dashed line indicates the inferred boundary of the HP (south) and UHP (north) terrains.

1) Xinjiang Bureau of Geology and Mineral Resources. Geological map of Quexiang sheet (K-44-16), scale 1: 200000. 1982

dimensions) and in places they are intercalated with schist. In southwestern Tianshan, the Atantayi Valley respresents the largest exposure location for HP metabasites, where both the HP and UHP eclogites were first reported in the region [5,10]. Numerous rock types are exposed along the river, including eclogite, blueschist and pelitic-felsic schist. Near the Atantayi river mouth, eclogite lenses and small-scale layers are common within the schists, whereas *in situ* massive blocks of eclogite and blueschist are only exposed in the upper part of this river.

## 2 Sample descriptions

We sampled three outcrops (including nearby loose blocks) along the Atantayi Valley (Figure 1(b)). More than 40 samples, composed of pelitic-felsic schists and mafic eclogites, were examined. Coesite and polycrystalline quartz inclusions in garnet were identified in four relatively fresh samples: 104-1 (Albite schist; GPS: 42°30′03″N, 81°16′01″E), 101-1 (Albite schist; GPS: 42°30′23″N, 81°14′50″E), AT103-2 (Eclogite; GPS: 42°31′54.6″N, 81°12′28.6″E) and AT103-6 (Albite schist; GPS location as for AT103-2). These coesite-bearing felsic schists are massive or well-foliated, consisting of albite, garnet, white mica, greenish amphibole (barroisite) and quartz (Figure 2(a),(b), Table 1). Oriented white mica, amphibole or epidote define the schistosity. Anhedral albite porphyroblasts include large numbers of inclusions, such as fine-grained euhedral-subhedral amphibole, relict white mica and rounded quartz. Porphyroblastic garnet is mostly euhedral, rarely rounded, and uniformly sized in one sample. However, its average grain size varies from sample to sample. Bluish amphibole (glaucophane) is usually overgrown by its greenish equivalent (barroisite). Coesite-bearing mafic eclogite mainly consists of fibrous oriented omphacite and porphyroblastic garnet (Figure 2(c)). Quartz is concentrated to form bands parallel to foliation or form strain shadows of the garnet. Other minor phases are rutile, clinozoisite, barroisite, white mica, albite and calcite.

The inclusion assemblages of garnet are the focus of this work, even though they are ubiquitously fractured and locally replaced by chlorite, biotite or carbonate. In addition to $SiO_2$ phases (see description below), other inclusions such as white mica, epidote, omphacite, rutile, amphibole and chloritoids are common (Table 1). Lath-shaped aggregates of epidote + white mica in garnet are assumed to be made of a pseudomorph of lawsonite (Figure 2(d)).

## 3 Coesite characteristics

In order to identify coesite and determine its typical texture, a detailed petrographic study was undertaken on well-polished thin sections of standard thickness, using both optical microscopy and *in situ* micro-Raman spectroscopy. The latter was performed on a Renishaw-RM1000 Laser Raman microprobe using the 514.5 nm line of an Ar-ion laser at Peking University. The laser spot size was focused to 1–2 μm. Accumulation times varied between 5 and 10 s. The estimated spectral resolution was 1.0 $cm^{-1}$ and calibration was performed using synthetic silicon.

Coesite inclusions in porphyroblastic garnet were identified from three samples: 104-1, 101-1 and AT103-2 (Figure 2(e)–(h)). Coesite is invariably surrounded by radial fractures within the host garnet, optically showing a higher relief than the surrounding quartz. Coesite usually constitutes 20%–60% of the total volume of the composite $SiO_2$ inclusions. The thickness of the quartz rim around each coesite inclusion varies substantially. A thin quartz rim, if visible, is palisade-textured, whereas a thicker one corresponds to polycrystalline quartz with a sutured subgrain boundary. Polycrystalline quartz, not accompanied by coesite, is also present in garnet, e.g. in samples 104-1 and AT103-6 (Figure 2(e),(i)). The grains that were optically identified as likely being coesite were further confirmed by Raman spectroscopy. They exhibit diagnostic bands for coesite at 428–426, 326, 271–270, 178–176, 151–150 and 121–118 $cm^{-1}$, in addition to 521 $cm^{-1}$ (Figure 3). For different coesite grains, a specific band may shift slightly for by 1–3 $cm^{-1}$. The diagnostic band for quartz at 464–468 $cm^{-1}$ is shown in all of the Raman spectra (Figure 3); however, its intensity significantly varies between different grains, implying the differential transformation of coesite into quartz.

## 4 Discussion

In contrast with many well-established UHP belts worldwide [1,13], evidence of UHP processes is scarce in the

**Table 1** Rock types and constituent minerals of the studied samples[a)]

| Sample | Rock type | Main minerals (in order of abundance) | Inclusions in garnet |
|---|---|---|---|
| 104-1 | albite schist | Ab + Grt + Brs + Qtz + Wm + Cb + Gln + Ttn + Ep + Chl | Coe + PCQ + Qtz + Lws-p + Rt |
| 101-1 | albite schist | Ab + Grt + Brs + Qtz + Wm + Ep + Ttn + Chl + Gln + Rt | Coe + PCQ + Qtz + Ctd + Lws-p + Rt |
| AT103-2 | eclogite | Omp + Grt + Cb + Rt + Qtz + Ep + Brs + Wm | Coe + Qtz + Lws-p + Omp + Brs + Ab + Rt |
| AT103-6 | albite schist | Ab + Brs + Grt + Qtz + Gln + Wm + Rt + Ttn | PCQ + Qtz + Lws-p + Rt |

a) Ab, albite; Grt, garnet; Brs, barroisite; Qtz, quartz; Wm, white mica (phengite and/or paragonite); Ep, epidote (or clinozoisite); Ttn, titanite; Gln, glaucophane; Cb, carbonate; Rt, rutile; Omp, omphacite; Chl, chlorite; Coe, coesite; PCQ, polycrystalline quartz; Ctd, chloritoid; Lws-p, lawsonite pseudomorph (replaced by epidote and paragonite).

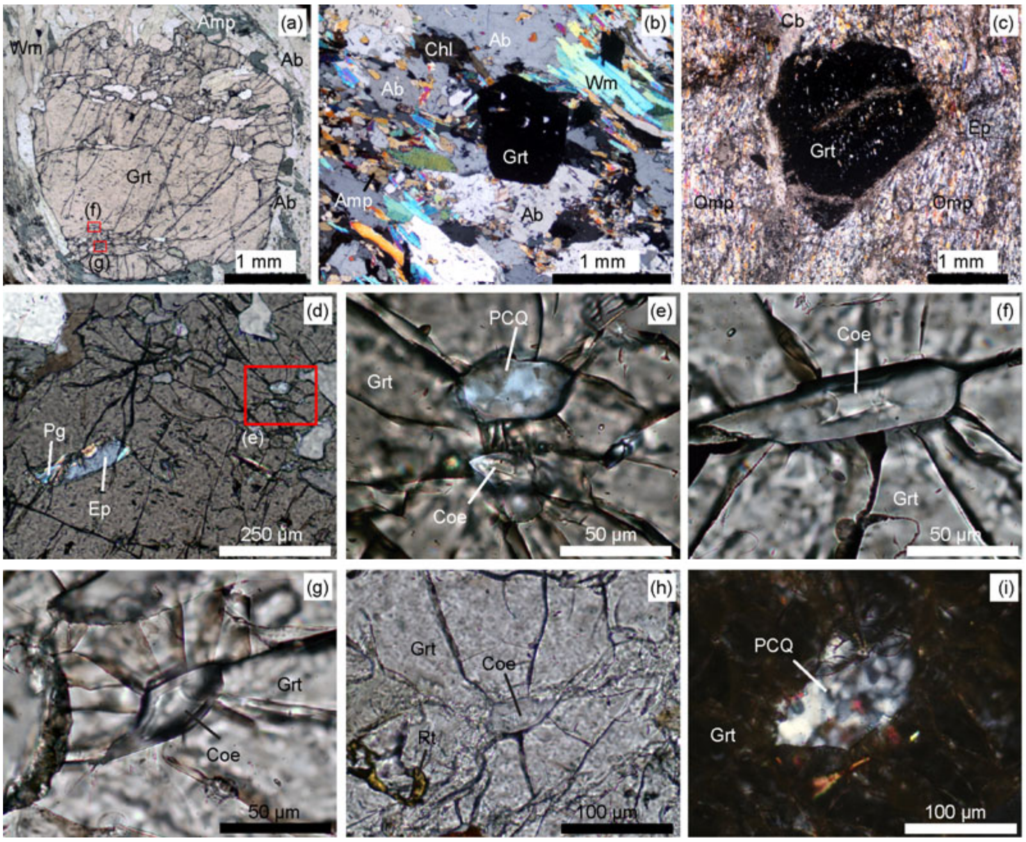


**Figure 2** Photomicrographs of studied samples. (a) Ceosite-hosting porphyroblastic garnet in sample 101-1 (plane polarized light); (b) albite, garnet and white mica in sample 104-1 (cross polarized light); (c) fibrous oriented omphacite, porphyroblastic garnet and secondary carbonate (calcite) in sample AT103-2 (cross polarized light); (d)–(e) coesite, polycrystalline quartz and lawsonite pseudomorph (Ep + Pg) in sample 104-1 (partially crossed polarizers); (f)–(g) coesite in sample 101-1 (plane polarized light); (h) coesite in sample AT103-2 (plane polarized light); (i) polycrystalline quartz in sample AT103-6 (cross polarized light).

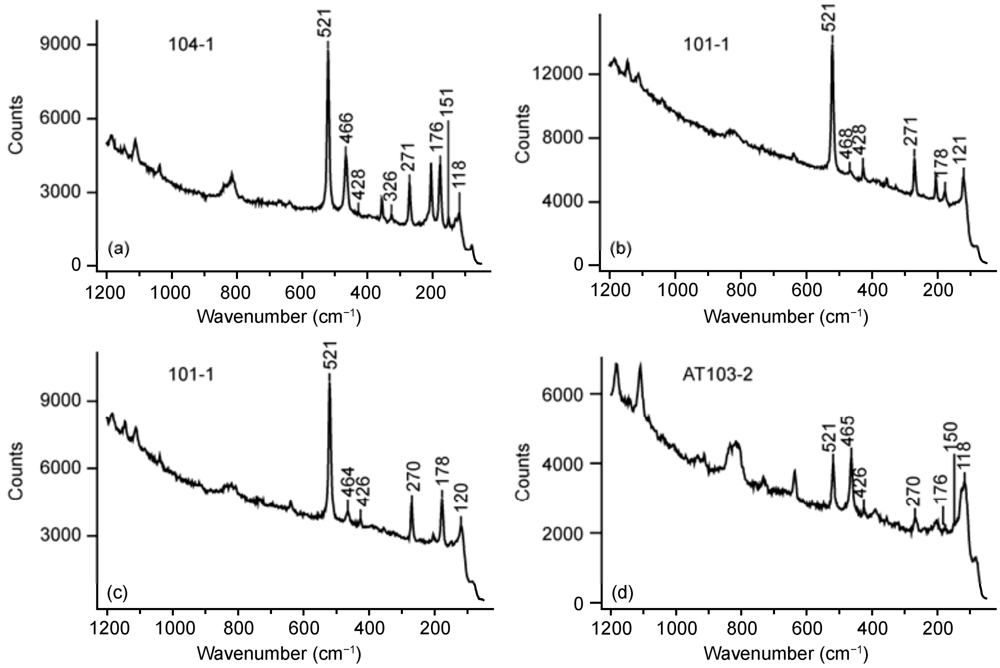


**Figure 3** Representative Raman spectra of coesite inclusions in porphyroblastic garnets from samples 104-1 (a), 101-1 (b), (c) and AT103-2 (d). Only the main diagnostic bands of coesite and one band of quartz (464–468 cm$^{-1}$) are labeled.

orogenic belt of southwestern Tianshan. To date, all optically identifiable coesite grains from the region have been enclosed in garnet. Although they are rare and have been transformed, to some extent, into polycrystalline quartz, this at least suggests that among the constituent minerals of schist and eclogite, garnet is key to effectively preserving evidence of UHP. In eclogite, even though some minerals are equilibrated texturally with garnet, they actually they may form during retrogression (e.g. barrioisite and paragonite, which usually enclose relict garnet and omphacite), or be subject to recrystallization (e.g. fibrous matrix omphacite). In schist, garnets are either embedded in albite, or surrounded by oriented white mica flakes—sometimes along with elongated amphibole and epidote. This texture suggests that peak phases are only available by searching fresh garnet inclusions. In addition to garnet, metamorphic zircon is also an excellent "pressure vessel" in preserving UHP minerals [14–16]. In the southwestern Tianshan orogen, largely due to relatively low peak temperatures, the metamorphic growth of zircon was usually depressed. It is rarely thick enough to be dated [17,18], with an average thickness of $< 10$ μm [19]. In this instance, even if an overgrown zircon were to form at UHP conditions, it would be difficult to effectively enclose an UHP mineral. However, searching for evidence of UHP within zircon separates is worthwhile in terms of precisely defining the UHP province of the southwestern Tianshan.

In this study, the characteristic texture of quartz secondary after coesite in garnet is generally visible. A thin quartz rim of less retrograde coesite usually exhibits a palisade texture. However, in most cases such a texture is not optically distinguishable due to its fine grain size, which is assumed to be formed prior to radial fracturing of the host garnet [20]. Strongly retrograde coesite occurs as relics that constitute a small portion of the whole $SiO_2$ inclusion, usually less than 20% in volume. Such coesite is immediately surrounded by polycrystalline quartz that develops an irregular mosaic texture. Where coesite completely disappears, the textures of the replacement polycrystalline quartz can be grouped into two types: (1) sutured mosaic and (2) polygonal mosaic. Quartz grains of the former type have variable size, curved boundaries and are characterized by irregular (patchy) undulatory extinction (Figure 2(e)). Quartz grains of the latter type have relatively straight boundaries and uniform size (Figure 2(i)). However, the abundance of each of these two types changes considerably between inclusions. As recrystallization progresses, polycrystalline quartz is transformed into monocrystalline quartz. Though surrounded by radial fractures, it is not appropriate to link this process to UHP metamorphism [21]. In one domain of porphyroblastic garnet, different $SiO_2$ phases, such as coesite, polycrystalline quartz and monocrystalline quartz are included. This supports the differential preservation of coesite during retrogression [20]. Therefore we conclude that the preservation of inclusions is dependent on their effective isolation by a host mineral. Related factors include the relative size of the inclusion and host, and the hardness and fracturing intensity of the latter. For Tianshan UHP rocks, petrographic studies show the resetting of schistosity during uplift, which tends to crack garnet, thereby enabling fluid ingress into the garnet and deleting most pristine coesite inclusions [22]. Even though coarse-grained garnet is strongly fractured, some segments remain large enough. This may prevent fluid infiltration and generate overpressure due to volume expansion during the coesite-quartz transition. However, garnets often experience a crack-seal process during exhumation, which makes the early retrograde fractures invisible. For instance, coesite in mafic eclogite can be found in such a garnet segment, as shown by an X-ray map [4].

The formation and evolution of UHP rock is a challenging subject in modern plate tectonic studies. This research is substantially based on investigating the scale of exhumed UHP terrains and their relationships with neighboring geological units. In southwestern Tianshan, coesite found in the Habutengsu Valley confirms the occurrence of UHP metamorphism [3,4]. However, because this is the only locality ever to have definitively reported evidence of UHP processes, the debate has been prolonged as to the areal extent of UHP metamorphism and the emplacement mechanism for Tianshan UHP eclogite [23,24]. Intensive external fluid has reacted with Tianshan eclogite during retrogression, as evidenced by blueschist facies overprints [25]. This fluid process also may happen to UHP eclogite, which would not only erase coesite from the eclogite but also enable the formation of blueschist rinds or veins [26]. Additionally, the multi-stage foliation of eclogites and schists indicates deformation that is coeval with retrogression, which greatly intensifies the retrograde metamorphism. Therefore, systematic work is required to clarify whether the coexistence of UHP and HP eclogites is a result of differential retrogression, or of tectonic mixing. New findings of coesite from the Atantayi Valley, reported in this study, suggest the predominant lithologies in the region have all experienced UHP metamorphism, which constrains an UHP terrain in southwestern Tianshan that extends up to 10 km N-S and 60–80 km E-W.

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