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Peperites in the Permian Tarim large igneous province in Northwest China and their constraints on the local eruption environments

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Peperites are special kinds of volcaniclastic materials generated by mingling of magma and unconsolidated sediments. They directly demonstrate the contemporaneity of volcanism and sedimentation, and hence they can be used to constrain the local paleoenvironments during volcanic eruptions. We identified peperites in the lower sequence of the northwest outcrops (Inggan-Kalpin area) of Permian Tarim large igneous province (TLIP), Northwest China. In Inggan, blocky peperites were observed at the base of lava flows generated in the second eruption phase. This kind of peperites is generated by quenching of magma in a brittle fragmentation mechanism. While in Kalpin, both the second and the fourth eruption phases preserved peperites in the base of lava flows. Not only blocky but also fluidal peperites can be observed in Kalpin. The fluidal peperites were generated in vapor films, which insulated the magmas from cold sediments and avoided direct thermal shock, and therefore kept the fluidal forms of magma. All of these peperites are hosted by submarine carbonates. In lava sequences generated in the same eruption phases but located in Kaipaizileike, ~15 km east to Inggan, terrestrial flood basalts developed while peperites are absent, implying a paleoenvironmental transition between Kaipaizileike and Inggan-Kalpin area. Gathering information from observed peperites, TLIP lava flows, and the Lower Permian sedimentary strata, we precisely constrained the spatial distribution and temporal evolution of sedimentary facies of the early stage of TLIP. As a result, two marine transgressions were identified. The first transgression occurred contemporaneous with the second eruption phase. The transition from submarine to subaerial is located between Kaipaizileike and Inggan. The second transgression occurred contemporaneous with the forth eruption phase, and the transition from submarine to subaerial occurred between Inggan and Kalpin.

peperite, Tarim, large igneous province, Permian, eruption environment, flood basalt

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Constraining the paleoenvironments during the generation of large igneous province (LIP) can provide great insight into issues such as crustal response to the mantle plume upwelling or interaction between flood volcanism and sedimentary environments. Large amounts (0.2×10^6–0.3×10^6 km^2 of Permian flood basalts (Chen et al., 1997; Tian et al., 2010; Yang et al., 2005; Zhang et al., 2010) are distributed in the Tarim Basin, Northwest China, which are generally seen as the main body of a Permian Tarim large igneous province (TLIP). The major part of TLIP is covered by sediments of the Tarim Basin. Outcrops are only seen in Kaipaizileike-Inggan-Kalpin locality, northwest of the Tarim Basin, Qipan locality of the southwest, and Mazartagh area in the center of the basin. Among these outcrop areas, the Kaipaizileike-Inggan-Kalpin locality has the best exposure

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from the lowermost to the uppermost succession of TLIP, providing valuable information for field study (Figure 1). According to fossil data in interlayers of TLIP, previous workers argued that the Northwest Tarim was mainly a terrestrial environment in the Early Permian, as is consistent with the macro tectonic evolution background which held a general marine regression caused by collision between the Tarim plate and Jungar plate (Sun et al., 1993; Wu et al., 1997). Studies on physical volcanologies of TLIP lava sequences suggested the lavas were emplaced in subaerial environments (Shangguan et al., 2012; Yu et al., 2010). Peperites observed, however, provide "sealed" and more precise evidence for paleoenvironment interpretations which may be different from what appear at the macro scales.

Peperites are products generated by mingling of magma and unconsolidated sediments (Skilling et al., 2002; White et al., 2000). Consequently they are constructed by two fundamental groups of materials: juvenile volcaniclasts and host sediments. During the mingling, magma chills and breaks into juvenile volcaniclasts. Either closely-packed or dispersed, these clasts are distributed in the fluidized sediments and hosted by them. As a genetic term (White et al., 2000), "Peperite" only refers *sensus stricto* to the mingling products of magma and unconsolidated sediments, and thus it gives a profound implication of contemporaneity of volcanism and sedimentation, from which the ancient environment can be deduced by the lithology of host sediments (Busby-Spera et al., 1987; Skilling et al., 2002; White et al., 2000). Here we report the identification of peperites in TLIP sequences in the Inggan-Kalpin area. Based on a detailed description of these peperites, we use them as a constrainer to understand the distribution and evolution of the local eruption environments of the northwest part of TLIP.

1 Geological background of TLIP

TLIP has an area of about 0.2 to 0.3 Mkm^2 (Chen et al., 1997; Tian et al., 2010; Yang et al., 2005; Zhang et al., 2010), the main body of which is the Tarim Permian flood basalts. Beside the basalts, there are also picrites, mafic tuffs, ignimbrites, andesitic basalts, rhyolites, and silicic tuffs preserved in the TLIP (Shanggguan et al., 2012; Tian et al., 2010), constituting a complete evolution from mafic magma materials to silicic (Chen et al., 2010). The intrusive systems of TLIP are seen mainly in Bachu, which conclude ultramafic complex (Jiang et al., 2004a; Jiang et al., 2004b; Yang et al., 2007a; Yang et al., 2007b), mafic dykeswarms (Zhang et al., 2012), bimodal dykes (Yang et al, 2007a), gabbros (Zhang et al., 2008), diorites (Zhang et al., 2008), syenites (Yang et al., 1996), quartz syenites (Zhang et al., 2008), and so on.

Different isotopic dating methods were utilized to reveal the age of TLIP. Chen et al. (1997) obtained an ^{39}Ar-^{40}Ar

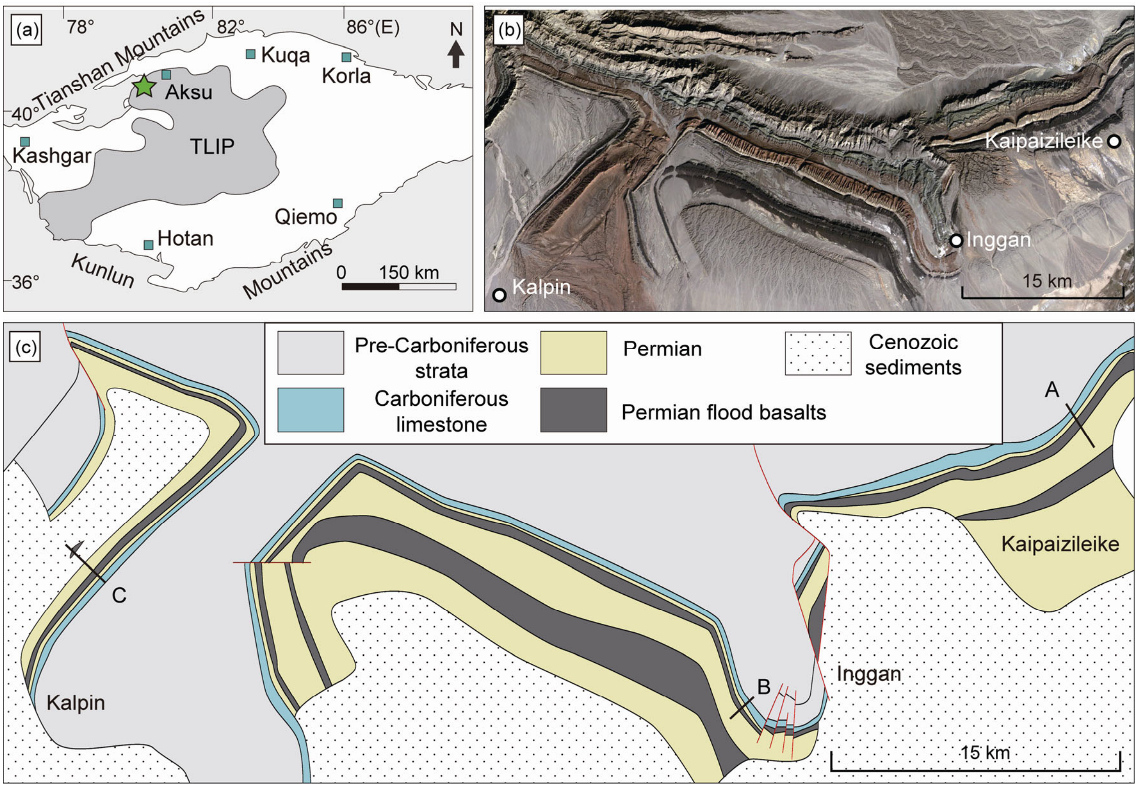

Figure 1 Geological background of the study area. (a) Distribution of TLIP; (b) remote sensing map of the Kaipaizileike-Inggan-Kalpin area; (c) geological map of the Kaipaizileike-Inggan-Kalpin area, in which A, B, and C represent the sections of the three localities logged in Figure 2.

age of 278.5±1.4 Ma in the flood basalts in Kalpin. Li et al. (2008) obtained a K-Ar age of 289.6 Ma in the flood basalts at the outcrops in southwest part of the Tarim Basin. Tian et al. (2010) reported a U-Pb age of 283–272 Ma to a rhyolite interlayers in TLIP. Yu et al. (2011) reported the SHRIMP U-Pb age of 289.5±2.0 Ma to 288±2.0 Ma as the timespan of Inggan TLIP sequences. Li et al. (2011) claimed the TLIP flood volcanism began at 290 Ma and ended at 285 Ma, and the intrusive complex developed during 284–274 Ma. Data in these geochronology reports show a consistency generally indicating that the TLIP volcanism is an Early Permian event. Geochemistry analysis indicated that the flood basalts of TLIP have ocean island basalts characteristics (Tian et al., 2010; Zhou et al., 2009), which were further suggested as a consequence of upwelling of an ancient mantle plume (Li et al., 2012; Zhang et al., 2010; Zhou et al., 2009). Supported by such comprehensive studies, this Permian intracontinent magma extruding system in Tarim hence correspond with the basic definition of LIP (Bryan et al., 2008), and therefore it is regarded as a new Permian LIP located just between Siberian Traps and the Emeishan LIP.

2 Northwest sequences of TLIP

The Kaipaizileike-Inggan-Kalpin area is located in the northwest edge of Tarim Basin (Figure 1(a)), where continuous strata from the Cambrian to Permian are well exposed. The Early Permian sequences, which completely conclude the TLIP flood basalts, conformably overlie a Carboniferous shallow marine limestone layer. Remote sensing and geological maps (Figure 1(b), (c)) clearly showed that the whole TLIP basalt sequences are separated into two subdivisions by hundred meters of sedimentary strata. The lower subdivision contains three eruption phases (EP1–3) and is regarded as the Kupukuziman Formation together with these hundred meters of sedimentary interlayers. All the Permian strata above the base of lavas in the fourth eruption phase (EP4) are considered as the Kaipaizileike Formation. The sedimentary sequences in these two formations are mostly homogenous, and the lithologies are grey lithic-quartz sandstone and siltstone, with mudstones and coals intercalated within them. Terrestrial botany fossils were preserved in the Early Permian clastic rocks, such as *Lepidodendron* sp. and *Stigmaria ficoides* (Sternberg) (Wu et al., 1997). Both the lithologies and fossils showed that the Kaipaizileike-Inggan-Kalpin area in the Early Permian was mainly a lacustrine sedimentary environment, which is consistent with the macro tectonic background that held that the Early Permian was an epoch of marine regression from east to west (Chen et al., 2006).

Newly found peperites and other observations of submarine environments, however, directly imply that the environment evolution during the emplacement of TLIP was remarkably rapid. These observations are all developed in succession under EP4. Volcanic products of the four eruption phases are described below:

EP1: The thickness of EP1 lava flow ranged from ~100 m in Kaipaizileike to ~20 m in Inggan-Kalpin (Figure 2). The thick lava sequence in Kaipaizileike shows a structural transition from columnar jointed massive basalts to high vesicular-amygdaloidal basalts. The relatively thin basalts in Inggan-Kalpin are generally massive without inner structural transition modeled by White et al. (2009).

EP2: The heterogeneity of the three localities is more remarkable. In Kaipaizileike, EP2 basalts generally display the same characteristics, especially well-developed columnar joints, as EP1 in the same section. Products of the two suits of lava flows are generally directly superimposed, with thin tuff lens less than 1 m locally intercalated in them (Shangguan et al., 2012). In Inggan, carbonate-hosted peperites developed at the base of the EP2 basaltic lava flows (Figure 2).

During the eruption interval between EP2 and EP3, ~22 m terrestrial sediment layers were deposited in Kaipaizileike,

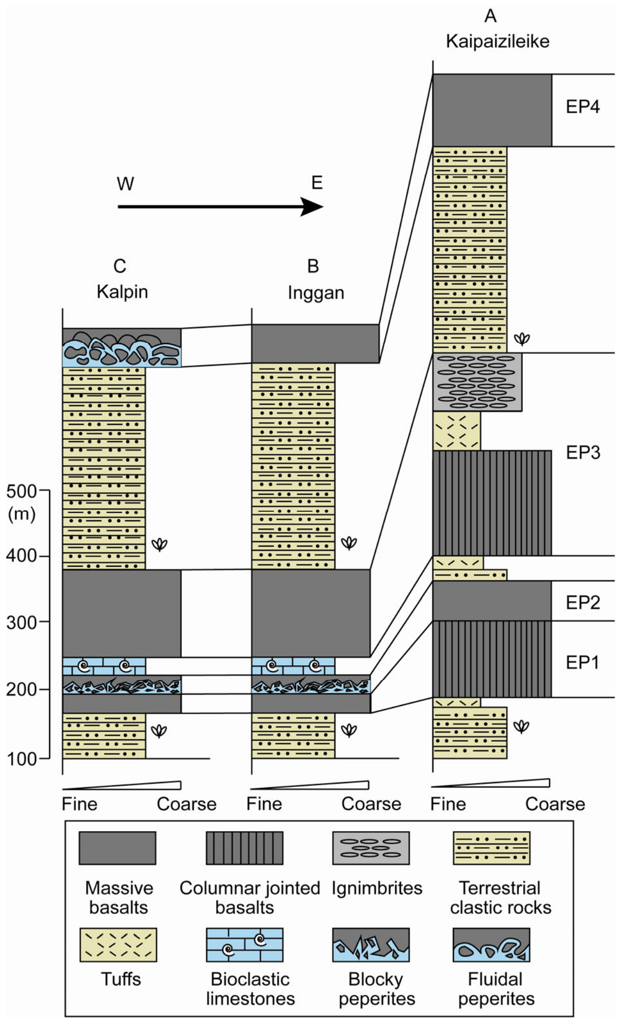

Figure 2 Column logs of Kaipaizileike, Inggan and Kalpin. Some information of the Kaipaizileike section accords to Shangguan et al. (2012).

sharply contacted with underlying and overlying lava flows. While in Inggan-Kalpin, the lithology changed to meters of marine fossil-bearing bioclastic limestones (Figure 3). Vitric tuff lens were preserved in the bioclastic limestone beds, with several centimeters in thickness. Influenced by Cenozoic tectonic movements of the Tianshan Mountains and covering by the Cenozoic sediments, the precise changing of lithofacies was obscured.

EP3 and EP4: During EP3, basaltic lavas in the three sections show the same characteristics of terrestrial pahoehoe flows. Above EP3 lava flows, all three sections have developed hundreds meters of terrestrial clastic rocks (Figures 1 and 2). From the beginning of EP4 recorded in the sections, the lava flow continued as terrestrial pahoehoe flows in Kaipaizileike and Inggan, which were never changed until the end of TLIP sequences. Yet in Kalpin, peprites are well developed in the EP4 pillow lava sequences. Above EP4, the Cenozoic sediments covered the Kalpin section. Hence no observation above EP4 can be seen in Kalpin.

3 Description of peperites

Peperites were found in outcrops in Inggan and Kalpin but none was identified in Kaipaizileike. In Inggan, peperites developed at the base of EP2 basaltic lava flow and in Kalpin, peperites were observed not only in EP2 but also in EP4 lava flows.

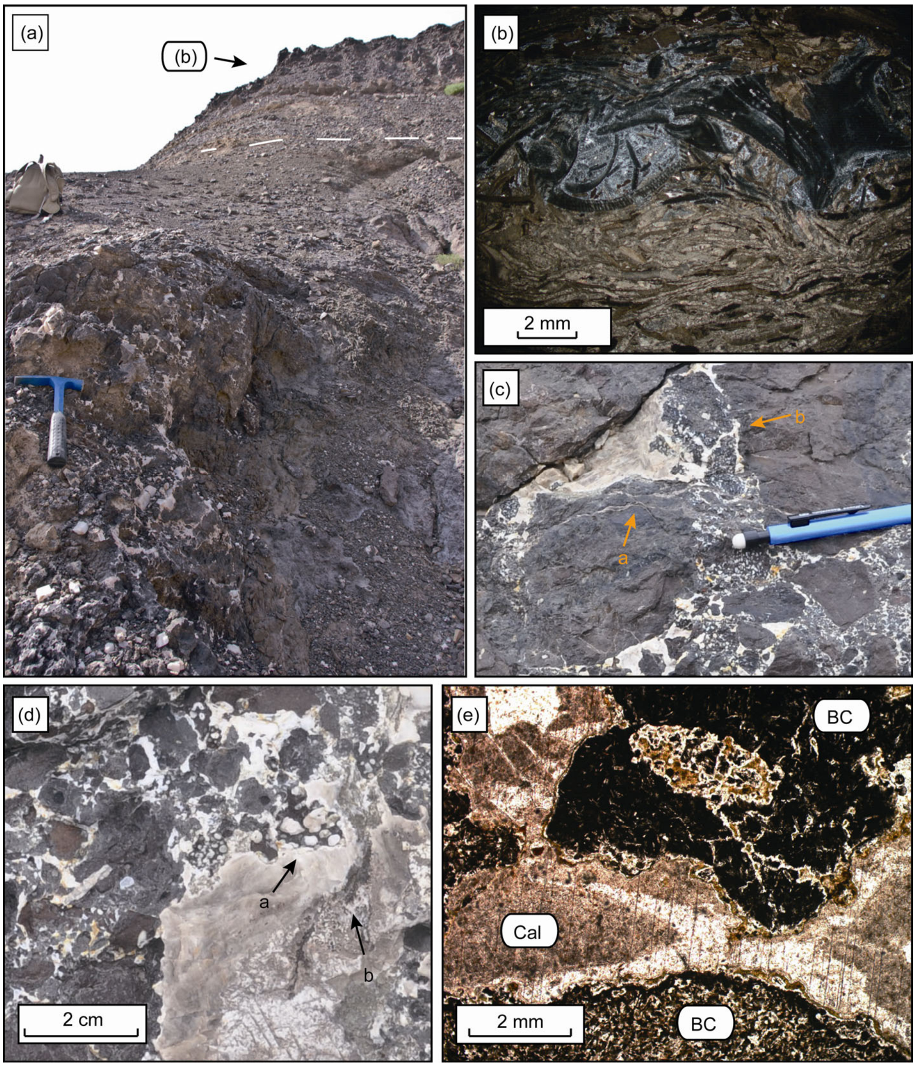

Figure 3 Observations of Inggan peperites. (a) Lava-foot peperites at the base of EP2 lavas. Above the EP2 lavas overlie the bedded bioclastic limestones; (b) microscopic photograph of the bioclastic limestones; (c) blocky, vesicle-free juvenile clasts of the peperites hosted by white carbonates, where the 'a' arrow indicates fractures of clasts filling by host sediments and the 'b' arrow indicates jigsaw-fit textures; (d) local textures of the blocky peperites, where 'a' arrow indicates a small fluidal clast sharing a small proportions in Inggan peperites, with carbonate sediments pocketed in its body and the 'b' arrow indicates elongated volcaniclasts which parallel with the fluidal laminations in the host sediments; (e) microscopic photograph of the blocky peperites. BC represents blocky clasts. Cal represents the calcites in host sediments. The clast in the low part has chilled margin with recrystallized calcite mantle in the sediments surrounding it. The clast in the upper part preserves jigsaw-fit textures.

3.1 Inggan peperites

Peperites in Inggan concordant with "lava-foot peperite" termed by Martin et al. (2007) refer to those developed at base of lava flows and generally parallel with the lava bed and the overlying limestone layer (Figure 3(a), (b)). The average thickness of the bedded peperite domain is about 10 m. The ratios of juvenile clasts/host sediments are generally high, ranging from 3:2 to 4:1. Juvenile clasts are grey to dark grey in color, centimeters in scale, and display blocky, tapered, polyhedral appearances. Based on the appearances of juvenile clasts, Busby-Spera et al. (1987) divided peperites into two classification groups: one was called "blocky peperite" (the clasts with blocky and polyhedral appearances) and the other, "fluidal (or globular) peperite" (the clasts with curved surface and generally globular, lobe or pillow-like forms). Therefore we identified the Inggan peperites as blocky peperites (Figure 3(c)), although a minor amount (<10%) of micro (<1–2 cm) clasts showing fluidal shapes can be seen locally among the blocky clasts (Figure 3(d)). The juvenile clasts are mainly vitrobasaltic to vitrophyric in textures. At the rims of some juvenile clasts, plagioclase phenocrysts show a parallel trend to the rims. Hydrothermal alteration products such as palagonites developed on the surface of some clasts. Blocky clasts are generally massive, with no vesicles and amygdal structures distributed inside (Figure 3(c), (d)). Minor proportions of clasts packaged some carbonate deposits in their inner spaces, with smaller vitric clasts mixed in the deposits. Close to the main body of lava flows or larger volcaniclasts, blocky clasts are distributed closely, forming the typical jigsaw-fit textures (Figure 3(e)).

The host sediments of Inggan peperites are marine carbonates (Figure 3(b)), which have already lithified into limestone. These host sediments are pure white, grey white or light yellow in color, filling in fractures among blocky clasts, packaged in the inner spaces of magma materials and supporting the smaller clasts. Locally the carbonates are partially recrystallized into macro calcite, developing cross-hatched twins. Some recrystallized belts occurred at the volcaniclast-sediments contact, parallel with the chilled margin of the clasts (Figure 3(e)).

3.2 Kalpin peperites

Kalpin peperites were observed at the base of EP2 and EP4 lava flows. The EP2 blocky peperites have similar characteristics as Inggan EP2 peperites. EP4 fluidal peperites are described below.

The EP4 fluidal peperites developed at outcrops in dry valley walls of a Cenozoic fluvial fan, associated with pillow-like lavas (Figure 4(a), (b), (c)). Due to the covering of Cenozoic sediments, the total thickness of peperites domain cannot be measured precisely. Typical fluidal peperites developed here, the juvenile clasts of which appeared fluidal (e.g., tailing) (Figure 4(c), (d)), globular (Figure 4(c), (e)) or pillow-like shapes (Figure 4(c)). These fluidal juvenile clasts have a high proportion of inner spaces (>30%), with recrystallized limestones being the same as the host sediments outside filling in them (Figure 4(c), (d), (e), (f)). Irregular and highly inner space-bearing clasts often have massive vitric textures with a few plagioclase phenocrysts and no chilled margin developed in the clasts. Other clasts that display closed curve surfaces, such as pillow-like and globular clasts, have obviously chilled margins (Figure 4(e)). They have a very small proportion of inner packing spaces and the plagioclases are highly developed (Figure 4(e)).

Like those in Inggan, the host sediments in Kalpin peperites are also white, locally recrystallized limestones. The original beddings of the limestones have been destructed by peperitic mingling. At the contact of sediments and fluidal clasts, secondary lamination of the limestone developed, parallel with the "fluidal" direction or elongation of the inner spaces and vesicles (Figure 4(d), (e)). The well-closed, chilled margin-beard clasts have recrystallized calcites developed in the hosts, which mantled the clast surfaces (Figure 4(e)).

Not only lava-foot peperites, but also peperites along the dyke intrusion are observed in the TLIP EP4 sequence, which are similar in appearance as those described by Martin et al. (2007) (Figure 4(f)). Kalpin peperites locally have multi-stage textures, such as fluidal appearances further being cut by brittle fractures and jigsaw-fit fragments (Figure 4(g)).

4 Discussion

4.1 Interpretation of peperites

Peperites are not simple physically-mixed products but associated with complex mechanisms such as fuel-coolant interactions (FCI) (White, 1996). Peperites generally developed at two typical locations in magma systems: either at the base of lavas flowing over unconsolidated sediments (lava-foot peperites) or at the magma-sediment contact in the dykes or sills that intrude into unconsolidated sediments. As described above, peperites in Inggan and Kalpin are generally lava-foot types. Beresford et al. (2001) suggested that density instability would occur when lavas have higher density flow over the sediments. Thus, lavas burrow into wet and unconsolidated sediments, driving the process of peperitic mingling. Since great amounts of magmatic heat have transferred between hot magmas and cold sediments, peperitic mingling would be a violent process which may even involve all the local sediments into the mingling regime if only little sediments were deposited during the short interval between frequent eruptions. In this case, practical outcrops would probably show a false appearance that no sedimentation existed between the "direct superimposition" of two lava layers. However, the preserved peperites in the lava sequences can reveal the existence of the 'lost' sedimentation.

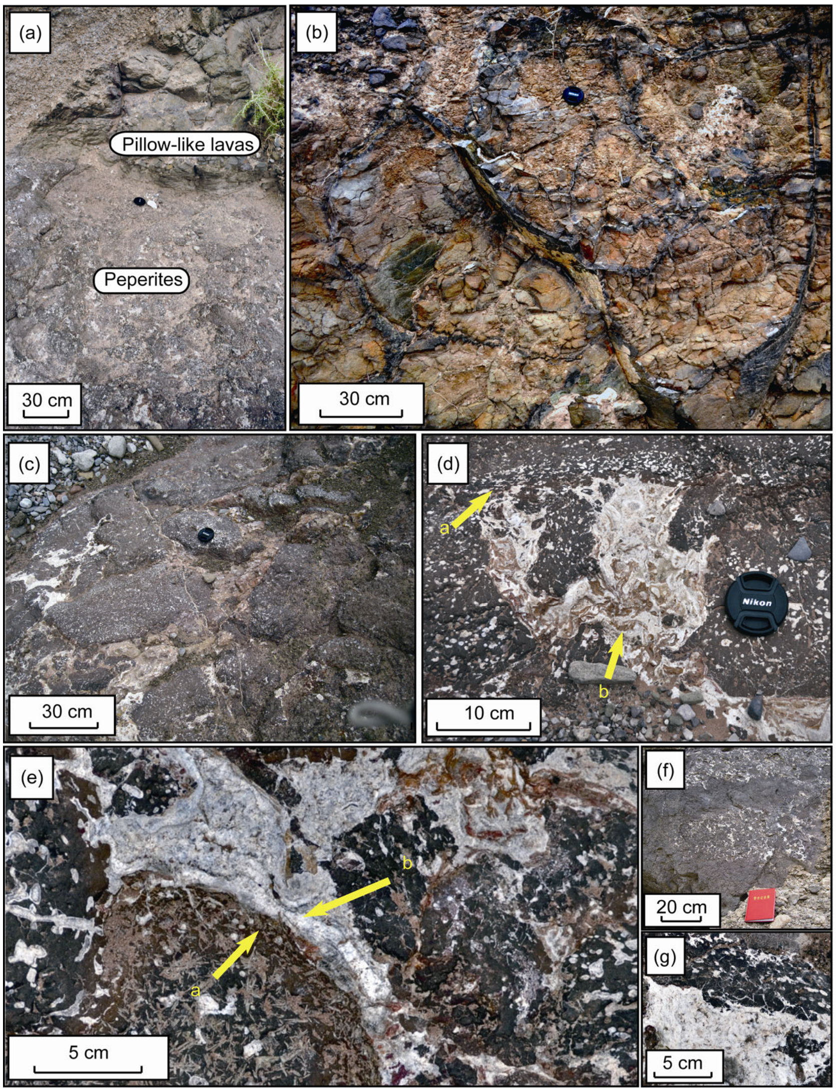

Figure 4 Observations of Kalpin peperites. (a) Fluidal peperites developed at the base of pillow-liked lava flows; (b) pillow lavas; (c) pillow-like clasts (dark brown) and fluidized carbonate sediments (light red and white) filling in them; (d) the fluidal peperites and hast sediments showing the same fluidal patterns. The 'a' arrow indicates the flowing appearance and paralleled sediment pockets in the magma body. The 'b' arrow indicates secondary laminations preserved at the contact of magma and sediments; (e) a pillow-like juvenile clast which has fewer sediment pockets and large proportions of plagioclases. Chilled margin developed at the rim of the clast (arrow 'a') and the paralleled recrystallized sediments mantled it (arrow 'b'); (f) peperitic lobes extended from a magma intrusion into the surrounding sedimnets, the peperitic region of which is similar with reports of Martin et al. (2007); (g) fluidal peperites are superimposed by brittle jigsaw-fit fractures.

Peperites are precise indicator that shows the contemporaneous volcanism and sedimentation, rather than the well bedded sediment layers set above or below the lava sequences. Similar cases with only peperites developed but no original sedimentary beds were also reported in peperitic domain in west Jungar (Chen et al., 2012).

Fluidization of sediments is a necessary condition for peperitic mingling. Therefore, only wet, soft and unconsolidated sediments (not the lithified sedimentary rocks) can fluidized and participate in mingling mechanism. Heated by magma, the pore water in the sediments transited into vapor phase that destructs original sedimentary structures and drives the sediment particles to move as a fluid (Kokelaar, 1982). Detail forming processes of blocky and fluidal peperites are different, yet both of them require the fluidization of sediments. The replacement of unconsolidated sediments by mingling magma needs fluidization of sediments, and the fractures that opened during fragmentation of magmas can be filled only by fluidized sediments (Kokelaar, 1982). Peperites in Inggan and Kalpin recorded such fluidized phenomenon of filling the fracture of magma, destruction of original sedimentary structures, and formation of secondary laminations in sediments that parallel to the flowing orientation of magma and wet sediments, which are all consistent with previous reports (Branney et al., 1988; Brooks et al., 1982; Goto et al., 1996; Kokelaar, 1982).

Blocky peperites are generated in a brittle fragmentation mechanism. When hot magma comes to be in contact with cold wet sediments, the magma chills by thermal shock, and mechanical stresses let the magma quench into blocky and vesicle-free juvenile clasts (Busby-Spera et al., 1987). Magmatic heat is transferred from magma to sediments, the pore water of which then vaporizes and drives the fluidization of sediments. These fluidized sediments then fill into the fracture spaces of new-fragmented clasts, forming the final pattern of blocky peperites (Figure 3(a), (c), (d), (e)) (Hanson et al., 1982; Kokelaar et al., 1986). Jigsaw-fit textures (Figure 3(c)) are the most typical textures of blocky peperites, which directly reflect in situ fragmentation and no further transportation of juvenile clasts (Skilling et al., 2002). Fractures of the jigsaw-fit textures are all filled with host sediments, directly indicating the fluidization and movement of sediments into the fractures (Brooks et al., 1982; Kokelaar, 1982). Usually the clasts of blocky peperites are closely-packed due to the *in situ* fragmentation. However, those cases of dispersing of clasts into host sediments may be driven by overheating of pore water of sediments that are enveloped into the magma body. The pocket explodes and casts magma fragments out into the hosts, producing dispersion structures of juvenile clasts (Busby-Spera et al., 1987).

The generation of fluidal peperite is different from blocky peperites because the latter calls for function of a stable maintained vapor film. Busby-Spera et al. (1987) suggested that when magma heats the sediments, the pore water changes into steam and forms a vapor film at the surface of magma. The vapor film would maintain stably at the magma-sediment contact if the sediments have a low permeability. It insulates the hot magma from cold sediments and therefore keeps the fluidal appearance of magma and avoids magma from thermal shock and quenching. Magma flows with the expansion of stable vapor film, and envelops sediments into small pockets of them, providing sediment-filled amygdal structures. This kind of “pocketed sediments” are unlike those developed in blocky clasts because insufficient time is provided. Consistent with such model, the Inngan blocky peperites are almost vesicle-free whereas the Kalpin fluidal peperites are rich in highly vesicled juvenile clasts (Figures 3 and 4).

The mixing or superimposition of blocky and fluidal peperites (Figures 3(d) and 4(g)) in the same location may be generated by the transition from fluidal to brittle behavior of magma with time, which was probably induced by the broken of vapor film, or increase of viscosity as the magma cooled down (Brooks et al., 1982; Chen et al., 2012). The relative proportion of the two clast groups may reflect the relative weight of the fluidal and brittle stage during peperitic mingling.

4.2 Interpretation of eruption environments

Peperites are direct indicators of subaqueous eruptions as well as the pillow lavas developed in the EP4 sequence in Kalpin. The carbonate host sediments of peperites and the bedded bioclastic limestone overlying EP2 lava flow further constrain the subaqueous eruptions as occurred in a submarine background.

Formations of the sedimentary interlayers within the lavas were not developed precisely contemporaneous with the volcanism recorded as the lavas, for the only deduction from the superimposed relationship between lavas and lithified layers is a successive arrangement of volcanism and interval sedimentation. Peperite is more precise in temporal constraining than layer successions, since the unconsolidated and wet characteristics of the sediments mingling with magma directly imply the volcanism occurred in an observable basin with certain sedimentary environments consistent with the lithology of host sediments. As the carbonate hosts in peperites are different from the main terrestrial clastic interlayers within TLIP sequences, the interpretation to the paleoenvironment must be dramatically different if these peperites were completely absent or unrevealed in the TLIP sequences.

Thus, a more precisely re-interpretation to the northwest part of TLIP can be proposed, given the new observation of peperites. After the wide deposition of carbonate platform products during Carboniferous, the first regression occurred at the beginning of Early Permian, consequently forming the first terrestrial lithic quartz sandstone layer of the Kupukuziman Formation. EP1 subaerial effusive lavas were emplaced after the onset of TLIP. This regression may be linked to the impinging of TLIP mantle plume (Saunders et al., 2007).

EP2 lavas and the overlying bioclastic limestone beds recorded the first transgression of seawater from west to east sites. TLIP volcanism in the Inggan-Kalpin area was emplaced under the sea level and mingled with submarine carbonate deposits, producing blocky EP2 peperites. While in Kaipaizileike of the east, EP2 columnar jointed lava sequences recorded a subaerial flood eruption, with the thick terrestrial sandstone directly overlying it.

Sea retreated again from the onset of EP3 to the onset of EP4, producing homogeneous lava flows in the three localities and depositing the thickest Kupukuziman terrestrial interlayers. The second transgression occurred during EP4, but the submarine environment only affected Kalpin, where pillow lavas and fluidal peperites developed, while the terrestrial environment are homogeneous from Inggan to Kaipaizileike. After the EP4 stage, no facies changing can be observed between Inggan and Kaipaizileike. Sections in the Kalpin locality are covered by the Cenozoic sediments, and thus no correlation can be made.

5 Conclusions

Peperites were identified in the lower TLIP sequence in Inggan-Kalpin area. Blocky peperites developed at the base of EP2 basaltic lava flows in Inggan and Kalpin, and fluidal peperites developed in the EP4 lava flows in Kalpin. All these peperites are generated by mingling of TLIP magma with submarine carbonate deposits, which also formed a stable limestone layer above the EP2 lavas. As a precise indicator for contemporaneity of volcanism and sedimentation, peperites directly imply that the EP2 and EP4 of TLIP occurred in a submarine environment.

The submarine environment in the early TLIP events was transited frequently with terrestrial lacustrine environments, as supported by the observations recorded in Kaipaizileike, ~15 km east of the Inggan-Kalpin area, where the volcanic facies suggested a terrestrial eruption background but no peperite and other evidence of a submarine environment can be identified. Two transgressions from west to east sites can be revealed during the TLIP event.

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