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Submarine pyroclastic deposits in Tertiary basins, NE Slovenia

Podmorski piroklastični sedimenti terciarnih bazenov severovzhodne Slovenije

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Abstract

In Tertiary basins of NE Slovenia, Upper Oligocene volcanic activity occurred in a submarine environment that experienced contemporaneous clastic sedimentation. Pyroclastic deposits are essentially related to gas- and water-supported eruption-fed density currents. At Trobni Dol, the Laško Basin, an over 100 m thick deposit formed by a sigle sustained volcanic explosion that fed gas-supported pyroclastic flow. Diagnostic features are large matrix-shard content, normal grading of pumice lapilli, collapsed pumice lapilli and the presence of charcoal.

In the Smrekovec Volcanic Complex, several but only up to 5 m thick deposits related to eruption-fed gas-supported pyroclastic flows occur. Deposits settled from water-supported eruption-fed density currents form fining- and thinning-upward sedimentary units which resemble the units of volcaniclastic turbidites. Pyroclastic deposits related to gas- and water-supported density currents occur in an up to 1000 m thick succession composed of coherent volcanics, autoclastic, pyroclastic, reworked volcaniclastic and mixed volcaniclastic-siliciclastic deposits that indicate a complex explosive and depositional history of the Smrekovec Volcanic Complex.

Izvleček

V terciarnih bazenih severovzhodne Slovenije je imelo vulkansko delovanje v celoti podmorski značaj in je potekalo istočasno s klastično sedimentacijo. Piroklastični sedimenti so večinoma vezani na gostotne tokove napajane iz vulkanskih izbruhov, ki so imeli kot intergranularno fazo bodisi plin ali vodo. Pri Trobnem Dolu v Laškem bazenu je nastalo preko 100 m debelo zaporedje piroklastičnih sedimentov z enim samim vulkanskim izbruhom. Piroklastični tok, katerega je napajal vulkanski izbruh je imel kot intergranularno fazo plin, zaradi česar se je počasi ohlajal. Prepoznavne lastnosti so velika vsebnost črepinjic vulkanskega stekla v osnovi, normalna gradacija plovčevih lapilov, lapili s porušeno notranjo strukturo in prisotnost zoglenele organske snovi.

V Smrekovškem vulkanskem kompleksu najdemo številne sedimentacijske enote nastale s piroklastičnimi tokovi, ki so se napajali iz vulkanskih izbruhov in so imeli kot intergranularno fazo plin, vendar so debeli le do 5 m. Poleg njih najdemo tudi sedimentacijske enote nastale z gostotnimi tokovi, ki so se prav tako napajali iz vulkanskih izbruhov, a so imeli kot intergranularno fazo vodo. Za te sedimentacijske enote je značilno manjšanje zrnavosti in tanjšanje plasti navzgor, ki je zelo podobno sedimentacijskim enotam nastalim z gravitacijskimi vulkanoklastičnimi turbitinimi tokovi. Zaporedje izlivnih vulkanskih kamnin ter avtoklastičnih, piroklastičnih, presedimentiranih vulkanoklastičnih in mešanih vulkanoklastičnih-siliciklastičnih sedimentov v Smrekovškem vulkanskem kompleksu je debelo do 1000 m in dokazuje njegov zapleten erupcijski in sedimentacijski razvoj.

Introduction

During the past three decades, significant advances have been made in recognition, study and monitoring of subaqueous explosive volcanism, nevertheless, the understanding of oceanic volcanic activity remains limited. The inability to actual witness entirely submarine eruptions, processes, styles, transport, lithofacies characteristics and the constraints on these means that the considerations are still largely inferential and based on a combination of theory, experimental work and interpretation of modern, and particularly ancient submarine volcanic successions (Fisher & Schmincke 1984; Cas & Wright, 1987; Busby-Spera, 1988; Bull & Cas, 1991; Cas, 1992; McPhie et al., 1993; Cole & Stanley, 1994; Wright et al., 1996; Schneider et al., 2001; Branney & Kokelaar, 2002; Manville et al., 2009).

Explosive eruptions are driven by volatiles of varying origin, although the other determinants are also relevant and include the properties of magma (e.g. composition, viscosity, eruption rate, volatile content), and ambient conditions, particularly pressure and the presence or absence of external water. The volatiles are commonly exsolving magmatic gases, such as water and carbon dioxide, and they trigger magmatic explosions (Cas, 1992). The presence of external water, which eventually becomes superheated and vapourised in contact with magma, may lead to hydrovolcanic (or phreatic) explosions. Volcanic explosions can be driven by a combination of exsolving magmatic volatiles and superheated external water, and they are collectively termed phreatomagmatic explosions (Peckover et al., 1973; Kokelaar, 1983). In submarine environments, the explosive expansion of volatiles may be suppressed by the ambient pressure that may be either hydrostatic in the case of an open vent on the seafloor or lithostatic plus hydrostatic where explosions commence below the sea floor (Cas & Wright, 1987). The estimated practical maximum depths for the explosive eruption of most magmas with known volatile contents are in the range of 500 m to 1000 m (McBirney, 1963); for hydrovolcanic and phreatomagmatic explosions they possibly do not exceed 700 m (Peckover et al., 1973).

In subaerial settings, primary pyroclastic deposits form as a result of explosive fragmentation of magma followed by single-stage transport through the ambient atmosphere. In subaqueous settings, the transport and depositional processes are controlled by the style of eruption and its interaction with the surrounding water. A significant advance in understanding of subaqueous pyroclastic deposits, based on modes of fragmentation and transport, has been done by White (2000). His modern conceptual division of density currents fed directly from explosive subaqueous eruptions includes explosive fragmentation of magma and deposition from gas- and water-supported currents. The concept has been applied in a comprehensive review of Tertiary volcaniclastic deposits in North-Eastern Slovenia as it further clarifies the distinction between pyroclastic deposits transported by the energy of volcanic activity, and texturally modified volcaniclastic deposits resedimented by post-volcanic subaqueous gravity-flows. The aim of the present article is to explain typical examples and their diagnostic features in order to facilitate lithofacies recognition in the field, particularly at detailed mapping and on site interpretation of borehole cores.

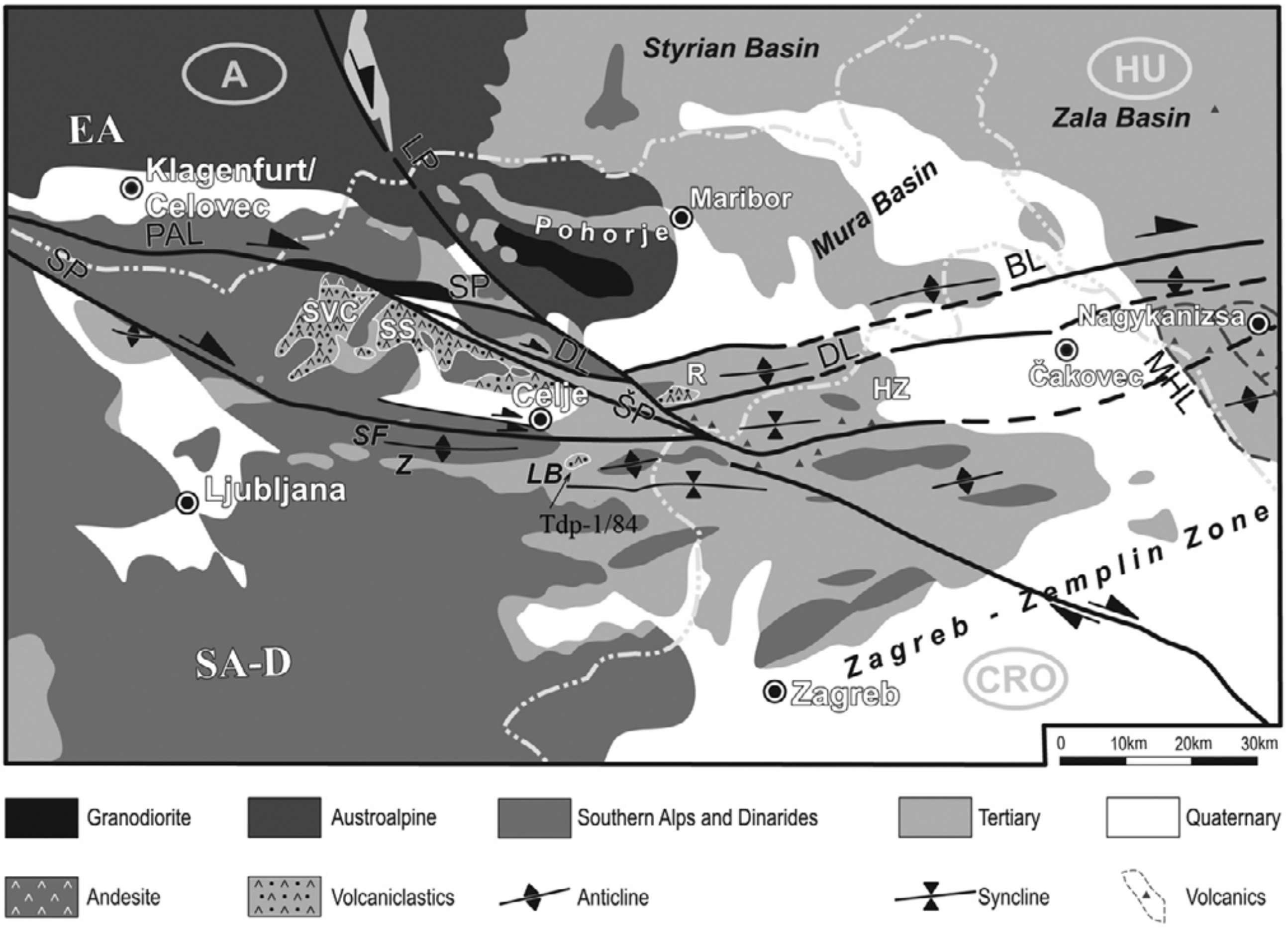


Fig. 1. Simplified geological map of North-Eastern Slovenia (after Mioč, 1978; Fodor et al., 1998; Jelen & Rifelj, 2002). EA - Eastern Alps; SA-D – Southern Alps and Dinarides; PAL – Periadriatic Line; BL – Balaton Line; MHL – Mid-Hungarian Line; DL – Donat Line; LP – Lavanttal (Labot) Fault; SF – Sava Fault; SP – Smrekovec Fault; ŠP – Šoštanj Fault; SVC – Smrekovec Volcanic Complex; SS – Smrekovec Series; LB – Laško Basin (with Trobni Dol); Z – Zasavje; R – Rogaška Slatina; HZ – Hrvatsko Zagorje (Croatian Zagorje)

Geological setting

The geological setting of North-Eastern Slovenia is rather complex (Fig. 1). In the area, there are three large tectonic units: the Southern Alps, the Dinarides and the Pannonian Basin. The main fault system is the Periadriatic Line which extends from the Western Alps to the south-western Pannonian Basin, and is characterised by Paleogene plutonic and volcanic rocks (von Blanckenburg & Davis, 1995). Along the easternmost surface extending, the Periadriatic Line splits into three local faults, termed the Smrekovec Fault, the Donat Line, and the Šoštanj Fault (Mioč, 1978; Fodor et al., 1998). They are assumed to be displaced along the Lavanttal Fault about 10 km southward, and to continue eastward under the cover of Tertiary sediments – the Smrekovec Fault as the Balaton Line, and the Šoštanj Fault as one of the faults of the Mid-Hungarian Line (Royden, 1988; Csontos & Nagymarosi, 1998; Fodor et al., 1998).

In palinspastic reconstruction, the Periadriatic Line represents a shear zone developed by subduction of the European plate below the African plate (Royden, 1988; Fodor et al., 1999, Kázmér et al., 2003). During Late Cretaceous and Early Eocene, the subduction changed into collision that uplifted the Alps (Dercourt et al., 1986). The following Late Oligocene to Neogene eastward continental escape from the collision zone in the Eastern Alps resulted in the formation of Alcapa and Tisia crustal blocks, which are separated by the joined Mid-Hungarian Line and Zagreb-Zemplin Zone (Royden, 1988; Csontos, 1995). Eastward progression of Alcapa and Tisia was accompanied by north-east to eastward translations and rotation, initiation of extensional strike-slip regime and development of the Pannonian Basin (Fodor et al., 1999). Neogene to Quaternary magmatism in the Pannonian Basin was generated in response to complex microplate tectonics and syn-sedimentary rifting in a back-arc setting, and produced calc-alkaline, shoshonitic and mafic alkalic rocks (Seghedi et al., 2005).

Oligocene volcanic activity in North-Eastern Slovenia is considered to be post-collisional and related to slab breakoff processes (von Blanckenburg & Davis, 1995). It seems to occur in the initial stage of extensional evolution of the Pannonian Basin, particularly during the activation of the Periadriatic Line (Pamić & Balen, 2001). Magmas erupted show calc-alkaline and medium-K affinity, and produced a suite ranging in composition from andesite to dacite and rhyodacite (Kralj, 1996; 1999).

On the territory of North-Eastern Slovenia, Oligocene volcanic deposits widely occur south of the Periadriatic Line in the Smrekovec Volcanic Complex (Kralj, 1996; 2012; Hanfland et al., 2004), and continue south of the Šoštanj Fault and along the Donat Line (Mioč, 1983) on the territory of Rogaška Slatina (Fig. 1). Toward the east, Egerian-Eggenburgian calc-alkaline volcanic rocks outcrop in the Croatian Zagorje (Altherr et al., 1995; Pamić & Balen, 2001), and merge under the cover of Tertiary and Quaternary deposits at the Croatian-Hungarian frontier (Zelenka et al., 2004). Oligocene volcanic deposits sporadically occur south of the Celje Fault (Fig. 1) in the Zagorje-Laško Basin, particularly at Trobni Dol and Košnica (Buser, 1978; Aničić & Dozet, 2002; Aničić & Juriša, 1985).

The Smrekovec Volcanic Complex forms a part of an ancient submarine stratovolcano edifice (Kralj, 2012) which has been dissected by the Periadriatic Line. According to Hinterlechner-Ravnik & Pleničar (1967) and Mioč (1983), the northern flank has been displaced toward the south, and today, it is positioned in the area of Rogaška Slatina. The uppermost part of the edifice has been eroded and lava flows, being more resistant than pyroclastic and volcaniclastic deposits, build the central mountain range with the highest peaks of Komen (1684 m), Krnes (1613 m), Smrekovec (1577 m) and Travnik (1637 m). In the central part of the complex, a variety of autoclastic, pyroclastic and resedimented volcaniclastic deposits occur, while in the apron, volcaniclastic and mixed volcaniclastic-siliciclastic deposits predominate (Kralj, 2012). The composition of magmas that created the Smrekovec volcanic Complex is mainly andesitic, only some late-stage deposits show dacitic affinity.

Along the margins of the Celje Basin at Zaloška Gorica, Gorenje and Velika Pirešica, and in the Zagorje-Laško basin at Trobni Dol and Košnica, pyroclastic flow deposits predominate. Dacitic to rhyodacitic vitric coarse-grained to lapilli tuffs are extensively altered to zeolites (Kralj, 1999). Their upper divisions commonly consist of reworked fine-grained volcaniclastic and mixed volcaniclastic-siliciclastic deposits interbedded with fine-grained marine silts.

Volcanic successions in Tertiary basins of the North-Eastern Slovenia have entirely submarine character and are commonly underlain and overlain by fine-grained fossiliferous clastic sediments, locally termed "sivica" (Kuščer, 1967).

Pyroclastic flow deposits from the Tdp-1/84 borehole, Trobni Dol

In the cored boreholes Tdp-1/84 and Tdp-2/84, located in the Laško Basin at Trobni Dol (Fig. 1) nearly 140 m thick volcaniclastic succession (Fig. 2) has been recognised. It consists of lapilli-, coarse- and fine-grained tuffs of rhyodacitic to rhyolitic affinity (Kralj, 1999), and is underlain, interbedded and overlain fossiliferous mudstone of the Upper Oligocene (Egerian) age (Petrica et al., 1995).

Pyroclastic flow unit from the Tdp-1/84 borehole is 107 m thick (Fig. 2) and originates from a single explosive event. Throughout the unit microforaminifers, fragments of coal and charred plant material occur. The lowermost division occurs between 149 m and 95 m of depth and consists of tuff breccia, lithofacies Bt. The largest clasts are cognate in origin and up to 30 cm long. They originate from the underlying volcaniclastic unit which was largely destroyed during the new eruption, and the clasts of tuff admixed to juvenile material. Matrix in tuff breccia is juvenile and consists of lapilli tuff rich in glass shards. Cognate fragments are altered to interlayered clay minerals and juvenile pyroclasts in clinoptilolite and montmorillonite.

Above a depth of 95 m, cognate fragments dissapear and juvenile material prevails. Between 95 m and 70 m massive lapilli tuff (mLT) occurs. Normal gradation of lapilli can be recognised, although fine-grained matrix remains entirely unsorted. The largest lapilli attain up to 7 cm, and their shape is commonly fluidal (Fig. 3), elongated in the flow direction or deformed in the Z-shape. Their internal texture is often collapsed. Some lapilli show peperitic texture (Fig. 4) and banded structure. The formation of such lapilli could be explained by local partial welding of pumice lapilli that incorporated some fine ash during the process of welding and progressive movement of the pyroclastic flow. Matrix of lapilli tuffs is coarse- and fine-grained vitric tuff. The main constituent are glass shards, many of them having typical Y-forms. Glass shards do not indicate welding.

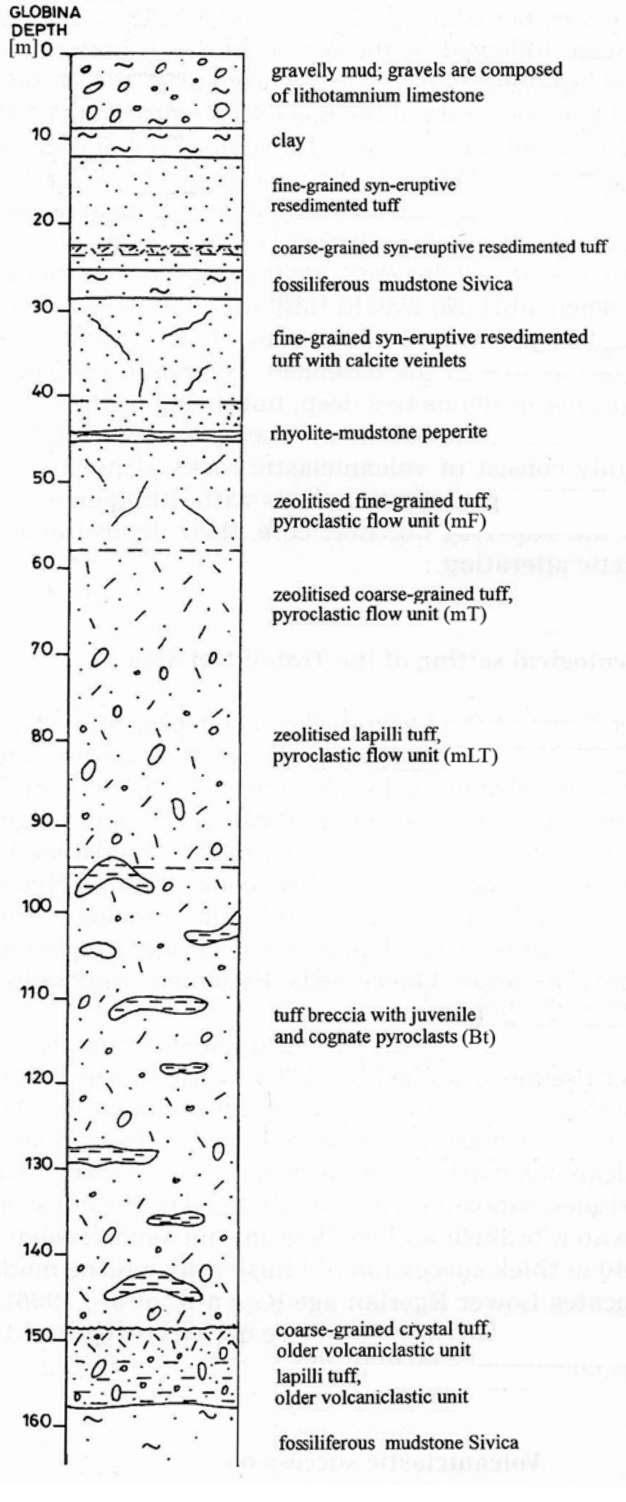


Fig. 2. Diagrammatic cross-section across the cored bore-hole Tdp-1/84 Trobni Dol

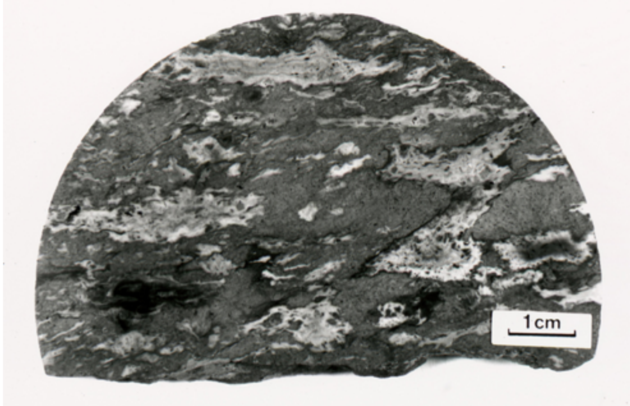


Fig. 3. Polished core surface from the borehole Tdp-1/84 at a depth of 83,2 m. Many lapilli have flame-like endings, and some of them are collapsed. Note extraordinary Z-shape above the scale

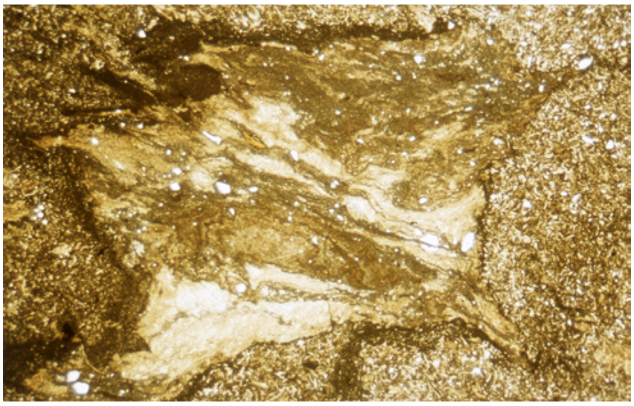
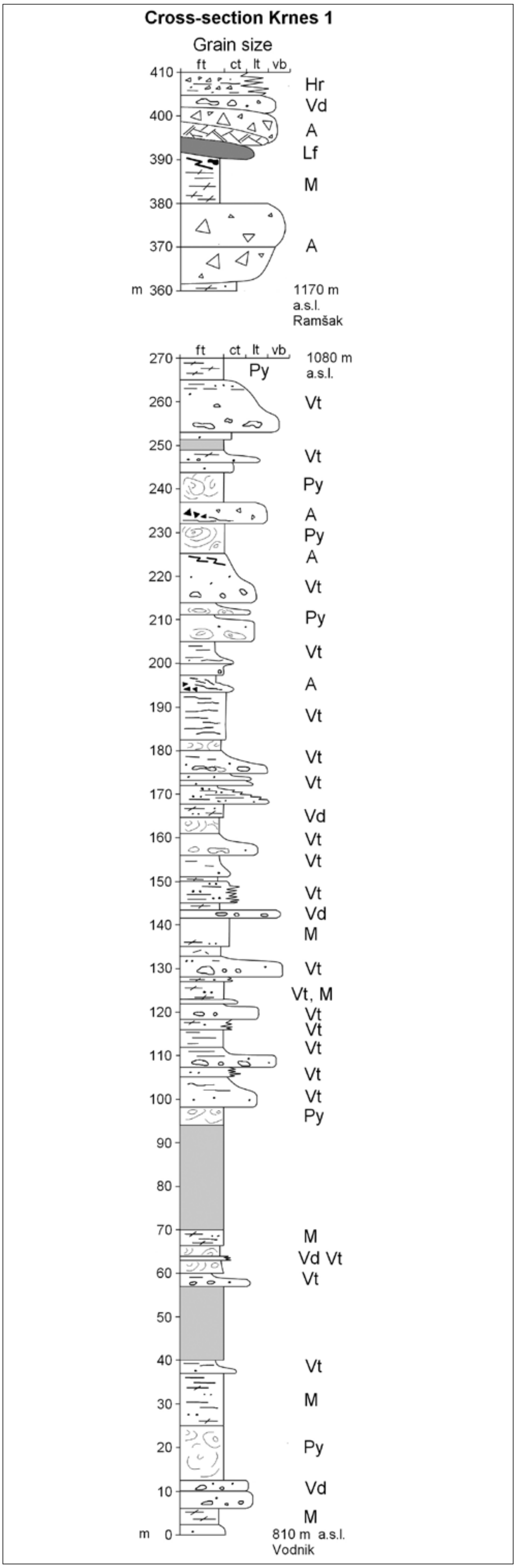


Fig. 4. Peperitic domain in a lapilli tuf, Tdp-1/84 at a depth of 83,5 m, formed by partial welding of a pumice lapilli and contemporaneous incorporation of fine-grained matrix. Plane-polarised light, the image length is 0,5 mm

At about 70 m of depth, lapilli tuff discretely grades into coarse-grained massive vitric tuff (mT), and from about 58 m upward, fine-grained massive (mF) and diffusely bedded tuff (dF) prevail. The pyroclastic flow unit terminates at a depth of 44,5 m with a rhyolite-mudstone peperite (P). The overlaying syn-eruptively resedimented fine-grained tuffs are horizontally bedded (hF) and interbedded by fossiliferous mudstone. Volcaniclastic succession terminates discordantly with eluvial clay and gravelly clay.

The cross-section Krnes 1, the Smrekovec Volcanic Complex

In the Smrekovec Volcanic Complex, pyroclastic, autoclastic and resedimented volcaniclastic deposits form a succesion with a complex lithofacies architecture that is clearly evidenced in the cross-section Krnes 1 (Fig. 5). Lithofacies groups and lithofacies occurring in the cross-section are summarised in Table 1 in addition to explanation to Figure 5 (Kralj, 2012).



Explanation

■ lava flow
▨ autoclastic lava flow
▨ hyaloclastite and hyaloclastite breccia, resedimented hyaloclastite
▨ peperitic breccia
▨ peperite (layers and pillows)
▨ volcaniclastic breccia an tuff-breccia
▨ massive lapilli tuff
▨ massive coarse-grained tuff
▤ bedded coarse-to fine-grained tuff
▨ graded thin beds of coarse-to fine-grained tuff
▤ fine-grained tuff and tuffaceous mudstone
▨ fine- and coarse-grained tuff
▒ covered

Grain size:
ft - fine tuff
ct - coarse tuff
lt - lapilli tuff
vb - volcaniclastic breccia and tuff-breccia

Lithofacies groups:
Lf - lava flow
A - autoclastic deposits
Hr - resedimented hyaloclastite deposits
Py - pyroclastic deposits
Vd - volcaniclastic debris flow deposits
Vt - volcaniclastic turbidity flow deposits
M - mixed volcaniclastic-siliciclastic deposits

Fig. 5. Simplified cross-section Krnes 1 with the subsections Vodnik and Ramšak, the Smrekovec Volcanic Complex

Table 1. Synopsis of the characteristics for volcaniclastic deposits in the Smrekovec Volcanic Complex

Lithofacies Group	**Lithofacies**	**Thickness**	**Initiation process**
Autoclastic deposits (A)	Autobreccia (AB)	1-5 m	*Quench fragmentation*
	Hyaloclastite breccia (HB)	1-5 m	*Quench fragmentation*
	Hyaloclastite (mH)	Several dm - 3 m	*Quench fragmentation, phreatic explosions*
	Peperite (P)		*Quench fragmentation and mixing and mingling with the enclosing wet sediment*
	Blocky peperite (PB)	0.5-3 m	
	Fluidal peperite (P)	< 1 mm - 1m	*Mixing and mingling of lava or magma and the enclosing wet sediment*
Pyroclastic deposits (Py)	Massive pumice lapilli tuff [mLT(p)]	Several dm–several m	*Gas- and water-supported eruption-fed density flows*
	Massive coarse- to fine-grained tuff [mT(p)]	3-20 cm	
	Massive to diffusely bedded tuff [dT(p)]	2-5 m	
	Horizontally bedded tuff [sT(p)]	Very thin to medium-thick beds	
	Horizontally laminated fine-grained tuff [sF(p)]	Laminae, in 1-20 cm thick unit	
	Cross-laminated fine-grained tuff [xF(p)]	Laminae, in 1-5 dm thick unit	
	Subtly lenticular fine-grained tuff [cF(p)]	Laminae, in 1-5 dm thick unit	
	Wavy laminated fine-grained tuff [vF(p)]	Laminae, in several cm thick unit	
Volcaniclastic debris flow deposits (Vd)	Polymict volcaniclastic breccia (Bx)	2-15 m	*Debris flows*
	Massive coarse-grained tuff (Sx)	0.3-5 m	*Sandy debris flows*
Volcaniclastic turbidite deposits (Vt)	Volcaniclastic tuff-breccia (Bt)	0.1-3 m	*Low-density turbidity currents and settling from suspension clouds*
	Massive lapilli tuff [mLT(v)]	Several cm – 0.5 m	
	Horizontally bedded coarse-grained tuff [hsT(v)]	Thin to medium thick beds	
	Horizontally bedded fine-grained tuff [hlF(v)]	Laminae, in 1-20 cm thick unit	
	Vaguely laminated fine-grained tuff [vlF(v)]	Laminae, in several cm thick unit	
	Cross-bedded coarse- to fine-grained tuff [xF(v)]	Laminae, in 5-15 cm thick unit	
	Massive fine-grained tuff [mF(v)]	1-25 cm	
Mixed volcaniclastic-siliciclastic deposits (M)	Massive tuffaceous sandstone [mS(v)]	Several mm - several cm	*Settling from suspension clouds, reworking by oceanic bottom currents*
	Horizontally laminated tuffaceous sandstone [hS(v)]	Laminae	
	Cross-bedded tuffaceous sandstone [tS(v)]	Several mm – several cm	
	Massive tuffaceous mudstone [mM(v)]	Several mm – several cm	

Eight lithofacies of pyroclastic deposits were recognised: (1) massive pumice lapilli tuff [mLT(p)], (2) massive coarse- to fine-grained tuff [mT(p)], (3) massive to diffusely bedded tuff [dT(p)], (4) horizontally bedded tuff [sT(p)], (5) horizontally laminated fine-grained tuff [sF(p)], (6) cross-laminated fine-grained tuff [xF(p)], (7) subtly lenticular fine-grained tuff [cF(p)]], and (8) wavy laminated fine-grained tuff [vF(p)].

Massive pumice lapilli tuff [lithofacies mLT(p)] is characterized by several decimeters to several metres thick beds (Fig. 6), but most commonly the thickness ranges between 1-3 m. The tuff is ungraded and consists of medium-sized (1-4 cm) lapilli, set in a matrix composed of glass shards, crystal grains and fine-grained, submicroscopic ash. Petrographic studies in thin sections have shown that pumice lapilli form from about 35-45 vol.%, glass shards and crystal grains 40-50 vol.%, and fine-grained ash 10-20 vol.% of the bulk rock, respectively. Crystal grains mainly belong to plagioclases; biotite is common as well, but occurs in very small amounts (<1-2%). According to the state of pumice lapilli, two subfacies have been recognised: massive pumice lapilli tuff with pumice that shows no sign of tube collapse or elongation (subfacies [$mL_1T(p)$]), and massive pumice lapilli tuff with pumice fiamme (subfacies [$mL_2T(p)$]).

Massive coarse- to fine-grained tuff [lithofacies mT(p)] is characterised by 3-20 cm thick beds, composed of glass shards, crystal grains and fine-grained ash, and very rare pumice lapilli (Fig. 7). Petrographic studies in thin sections have shown that glass shards are the most abundant constituent and commonly attain 40-50 vol.% of the bulk rock. Fine-grained ash amounts to 30-40 vol.%, crystal grains up to 10-15 vol.%, and pumice lapilli up to 5 vol.% of the bulk rock, respectively.

Massive to diffusely bedded tuff [lithofacies dT(p)] consists of several decimeters to several metres thick units; most commonly the thickness ranges from 2-5 m (Fig. 8). Basal contacts with the substrate are typically highly erosive and show evidence of scouring up to 0.8 m deep. The rock is essentially massive; indistinct and discontinuous bedding is indicated by a slight change in color and/or grain size. The tuff is mainly composed of ash-sized glass-shards, whilst fine-grained matrix forms up to 25 % of the bulk rock. Very commonly, there is an indistinct upward grading from coarser-grained division to somewhat finer-grained division. The tuff is well lithified. Combined petrographic studies and X-ray analysis of powdered samples have shown that clinoptilolite and cristobalite crystallized, and replace glass shards and fill interstices and vesicles. Columnar jointing locally occurs. Diffusely bedded tuff contains scarce foraminifera.

Horizontally bedded tuff [lithofacies sT(p)] is characterized by very thin- to medium-thick beds, composed of ash-sized pyroclast and/or fine-grained matrix (Fig. 8). In coarser tuffs, normal grading is common, and crystal grains are most often concentrated at the base. The division of horizontally bedded tuffs ranges in thick-

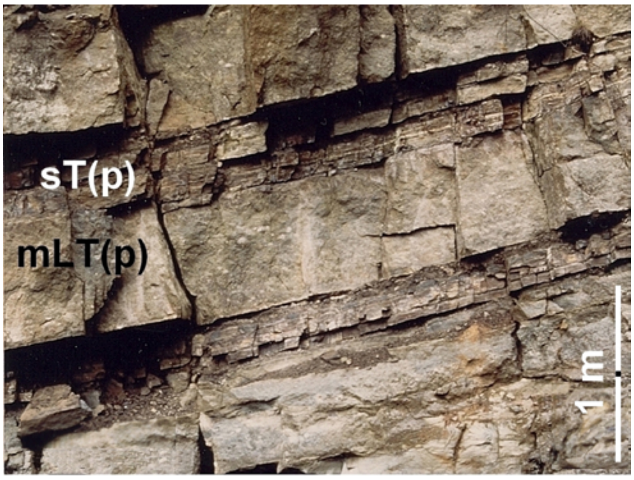


Fig. 6. Pyroclastic deposits showing a succession of Type 1 PDUs. The massive division mLT forms over half of the bulk PDU

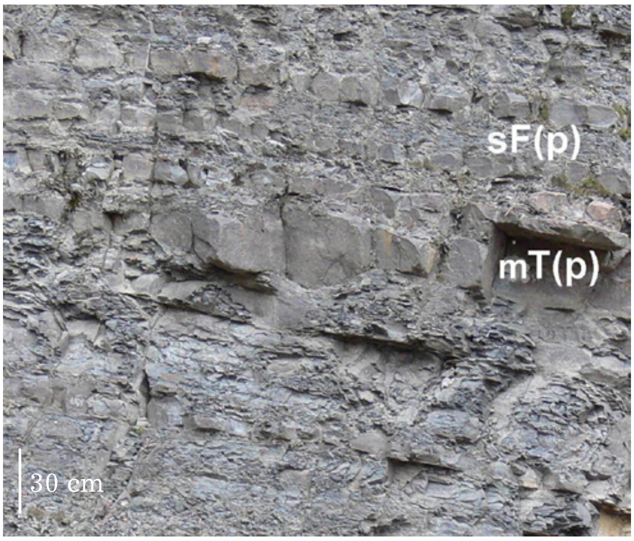


Fig. 7. Type 2 PDU, the cross-section Krnes 1, sub-section Vodnik

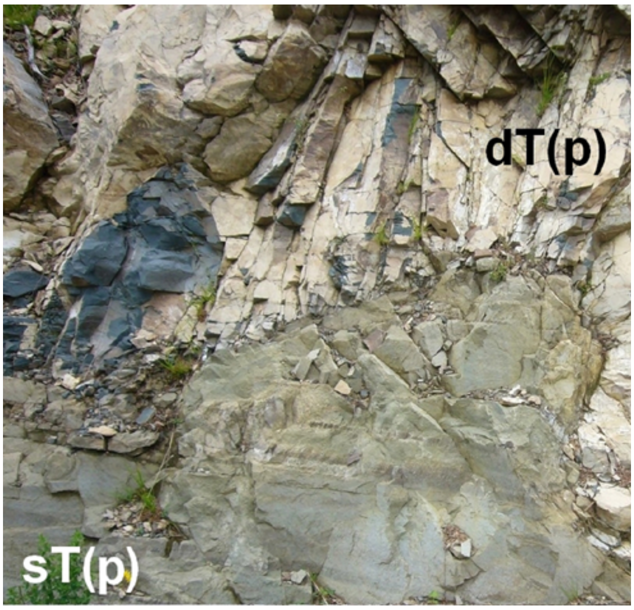


Fig. 8. Scoured, erosive boundary between Type 1 PDU (at the base) and the overlying Type 2 PDU. Hammer (33 cm) is for scale

ness from several cm to several decimeters, and an overall upward decrease in bed thickness and grain-size is common.

Fine grained tuffs consist of altered glassy ash and small crystal grains. The division of horizontally laminated tuff [sF(p)] varies in thickness from about 1-20 cm (Fig. 6, 7, 8). Cross-laminated fine-grained tuffs [xF(p)] form high- and low-angle cross-beds, and sometimes, sigmoidal dunes. They are commonly associated with subtly lenticular [cF(p)] fine-grained tuffs. The division of cross-bedded and subtly lenticular lithofacies ranges in thickness from 1 to 5 dm. Wavy laminated fine-grained tuffs [vF(p)] most often occur at the top of horizontally bedded division and form a unit several cm thick.

Discussion

Subaqueous pyroclastic flows commonly result from sustained explosive eruptions. Above the vent, explosively fragmented magma forms gas-thrust column and feeds laterally moving hot, gas-supported flow from which water is excluded by column gases. The current is driven by the excess density of the current relative to water, and therefore requires a very high particle concentration to overcome the low density of the continuous gas phase (White, 2000). In deep-water environments, gas-thrust columns formed by sustained eruptions of strongly fragmented pyroclastic material may be supressed owing to a high confining hydrostatic pressure upon gas expansion (Kokelaar & Busby, 1992). The flows fed from these supressed columns are initiated with high-particle concentrations, and flow-interaction with the surrounding water is mediated by stripping of low-particle concentration zones from the top of the flow and by a transient vapor barrier surrounding the main body of the flow (Kokelaar & Busby, 1992). Hydroplaning of advancing high-concentration flows may be disrupted at barriers and may result in isolated tuff bodies or slowing of flow-front advance and inhibition of hydroplanning (Howells et al., 1985).

Diagnostic features of subaqueous gas-supported pyroclastic flows are massive, unsorted deposits, collapsed pumice fiamme, plastically deformed glass shards and the evidence of heat retention such as welding textures, clasts with thermoremanent magnetic orientation or thermally altered organic matter. (Fisher & Scmincke, 1984; Cas & Wright, 1987; White, 2000).

Water-supported subaqueous pyroclastic flow deposits or eruption-fed aqueous density currents form when explosively fragmented erupting magma feeds hot clasts into water-supported turbidity currents and granular flows (White, 2000). The eruptions are intermittently explosive and commonly produce tephra jets. The currents may be diluted to highly concentrated, they are essentially turbulent and have water as the continuous intergranular phase. Typical depositional unit formed by a single eruption consist of a massive basal layer overlain by a thinning and fining upward set of beds, thinner than the basal layer (Fiske & Matsuda, 1964; White, 2000). The pulses of intermittent tephra jets may produce thin beds showing a variety of tractional current structures such as scours and cross-lamination (White, 2000). Water-supported density currents fed by subaqueous eruptions are similar to the gravity flows originating by sediment failure on steep slopes that must evolve from debris flows by ingestion of water (Sohn et al., 2002; White, 2000). The distinction is often very difficult and sometimes practically impossible, and sholud involve detailed petrography, mineralogy and geochemistry of deposits (Kralj, 2012).

The succesion in the cored borehole Tdp-1/84 at Trobni Dol has been interpreted as gas-supported pyroclastic-flow deposit. Diagnostic characteristics are thickness, coarse-tail grading, large matrix-shard content, collapsed and deformed lapilli, lapilli with peperitic texture and banded structure, and the presence of charcoal.

The interpretation of pyroclastic deposits in the Smrekovec Volcanic Complex needs and introduction of pyroclastic depositional units (PDUs) based on lithofacies architecture. Two varieties, Type 1 PDU and Type 2 PDU, have been distinguished.

Type 1 PDU is more common in occurrence (Figs. 6, 7). The thickest units attain up to 5 m. In thicker units, lithofacies $mL_1T(p)$ occurs at the base, and is overlain by the intermediate, horizontally bedded division, composed of lithofacies sT(p), which becomes upward more thinly bedded and finer-grained. Some coarser lithofacies sT(p) occurring at the base of thicker bedded divisions are amalgamated. Thicker Type 1 PDUs are commonly topped by [sF(p)] or [vF(p)] and [sF(p)]. In thicker units, massive division predominates and forms from 60-80 % of the bulk pyroclastic depositional unit.

The formation of thicker Type 1 PDUs is interpreted to be related to deposition from water-supported eruption-fed density flows. Diagnostic is massive basal layer, and the overlying fining and thinning upward set of beds. The composition is dominated by juvenile pyroclasts. Internal structure is practically identical to the units of volcaniclastic turbidites (cf. Bouma, 1962; Postma, 1986; Fisher, 1991; Schneider, 2000; Schneider et al., 2001).

Thinner Type 1 PDUs attain up to several decimeters (Fig. 7). In general, lithofacies $mL_1T(p)$ is absent and mT(p) occurs instead. Bedded division is thinner and finer-grained as well, and bed amalgamation is very rare. Horizontally bedded division may be overlain by sT(p) and sF(p), or by the division of cross-laminated [xF(p)] and subtly lenticular lithofacies [cF(p)], or by wavy laminated lithofacies [vF(p)]. Horizontally laminated fine-grained tuff [sF(p)] occurs at the Type 1 PDU's top, either directly overlying the bedded division or the division of cross-laminated and subtly lenticular and/or wavy laminated tuffs. Bedded and laminated divisions commonly form over 60 % of the bulk unit. Thinner units often occur in sets. Thinner sets are composed of few units while the thickest may consist of over fifty units and are over 20 m thick (Fig. 7). Sets of thinner 1 PDUs are very possibly deposits of density currents fed by intermittent tephra jets resulting from hydrovolcanic eruptions.

The Type 2 PDU is less abundant in occurrence (Figs. 8, 9, 10). Thicker units attain several metres and are composed of lithofacies mL$_2$T(p) at the base. Transition into the overlying lithofacies dT(p) is indistinct and gradual. Lithofacies dT(p) may show indistinct grading from somewhat coar ser ash-sized tuff at the base and somewhat finer ash-sized tuff at the top. Lithofacies dT(p) is overlain by sF(p), and there is a sharp distinction in the degree of lithification, colour and internal structure. Whilst mL$_2$T(p) and dT(p) are very well lithified and dark-green, the overlying sF(p) is much softer and brownish, and columnar jointing never continues from mL$_2$T(p) and dT(p) to sF(p). Hydroplaning of advancing high-concentration flows is often disrupted or inhibited at barriers and results in isolated tuff bodies (Figs. 8, 9, 10).

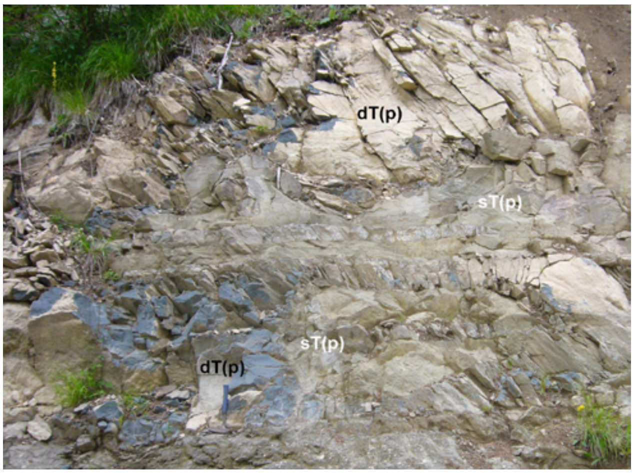


Fig. 9. A residual entrapped clast of the bedrock in the gas-supported eruption-fed pyroclastic flow. The obstacle supressed hydroplanning of the flow. The cross-section Krnes 1, sub-section Vodnik. Hammer (33 cm) is for scale

Fig. 10. Gas-supported eruption-fed pyroclastic flow – lithofacies dT(p) - scoured the unconsolidated volcaniclastic deposit (Bt) and underwent partial mixing along the contacts. The remaing tuff (I) is the entrapped and rolled material of the pyroclastic flow. The cross-section Krnes 1, sub-section Vodnik. Hammer (33 cm) is for scale

Conclusion

Upper Oligocene volcanic activity in sedimentary basins in North-Eastern Slovenia had entirely submarine character. Various lithofacies of pyroclastic deposits developed and they can be subdivided into two principal groups with respect to the origin either from gas- or water-supported eruption-fed density currents. An over 100 m thick succession composed of rhyodacitic to rhyolitic pumice lapillit tuffs and glass shard-rich tuffs at Trobni Dol is a typical example of gas-supported pyroclastic flow deposit. The lack of sorting of fine- to coarse-grained tephra, collapsed and plastically defomed pumice lapilli, and the presence of charcoal are the main diagnostic features. In the Smrekovec Volcanic Complex, both gas- and water-supported eruption-fed density currents occurred. Deposits settled from gas-supported pyroclastic flows and fed by sustained eruptions are much thinner than at Trobni Dol and attain up to 5 m in thickness. From water-supported eruption-fed density currents fining and thinning upward units deposited, and they are very similar to volcaniclastic turbidites originating from gravitational collapse. The distinction between pyroclastic deposits originating from water-supported eruption-fed density currents and genuinely reworked volcaniclastic turbidites is very difficult and often involves detailed analysis of field relations, lithofacies architecture, and structure, texture and composition of rocks.

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