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Role of trace element Pedogeochemistry in Diamond Exploration- A first Report from Lattavaram Kimberlite Cluster, Wajrakarur Field, Eastern Dharwar Craton, southern India

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RESUMO

O entendimento das tendências na concentração de elementos traço selecionados em solos residuais em quatro chaminés de kimberlito diamantíferos conhecidos (3, 4, 8 e 9) que ocorrem em Lattavaram dentro do Campo de Kimberlite de Wajrakarur (WKF) é tentada pela primeira vez. As chaminés 3 e 4 estão expostas enquanto os 8 e 9 estão ocultas sob calcrete e colúvio. Para este propósito, elementos como Nb, Cr, Ni, Co, Zr, Mg, Sr e La são usados para entender suas concentrações nos solos quimberlíticos em comparação com solos graníticos considerados *background*. Observa-se que os solos nos tubos de kimberlito apresentam enriquecimento conspícuo de elementos como Cr, Co, Nb, Ni, Mg e Sr quando comparados aos solos de granitoides. No entanto, não há muita variação nos padrões de elementos La e Zr entre os solos kimberlíticos e do background. O pulso alto em elementos traço em solos é atribuído à presença de minerais kimberlíticos primários e seus produtos de intemperismo no solo. Este aspecto particular da pedogeoquímica é considerado útil como uma ferramenta de exploração em busca de kimberlitos em partes cratônicas do sul da Índia. Um enriquecimento do conteúdo de Nb até 45 ppm em solos residuais pode ser considerado anômalo nas partes do subcontinente indiano, o que precisa ser confirmado e levado adiante em conjunto com mapeamento geológico de alta resolução, geofísica seguida de perfuração para confirmação de kimberlito/ocorrência de lamproite

ABSTRACT

Trends in concentration of selected trace elements in residual soils on four known diamondiferous kimberlite pipes (3, 4, 8 and 9) occurring at Lattavaram within the Wajrakarur Kimberlite Field (WKF) is attempted for the first time. The pipes 3 and 4 are exposed whereas the 8 and 9 are concealed under calcrete and colluvium. For this purpose, elements like Nb, Cr, Ni, Co, Zr, Mg, Sr and La are used to understand their concentrations in the kimberlitic soils in comparison with background granitic soils. It is observed that the soils on kimberlite pipes show conspicuous enrichment of elements such as Cr, Co, Nb, Ni, Mg and Sr when compared to soils in the country rock granitoid. However, no much variation in the elements La and Zr patterns between the kimberlitic and background soils is noticed. The high pulse in trace elements in kimberlitic soils is attributed to the presence of primary kimberlitic minerals and their weathered products in the soil. This particular aspect of pedogeochemistry is envisaged to be useful as an exploration tool in search of kimberlites in cratonic parts of southern India. An enrichment of Nb content upto 45 ppm in residual soils may be considered as anamolous in the craonic parts of Indian subcontinent, which needs to be confirmed and taken forward in conjunction with high resolution geological mapping, geophysics followed up by drilling for confirmation of kimberlite/lamproite occurrence.

Keywords: Soil, Geochemistry, Pedogeochemistry, Trace elements, Lamproite, Kimberlite, Diamond exploration, WKF, India.

1. INTRODUCTION

Diamond exploration, in the initial reconnaissance stages, involves searching for primary source rock i.e. kimberlite, using indicator mineral surveys coupled with airborne geophysical surveys. Kimberlite intrusions occur in the form of cylindrical intrusions called pipes, which are small circular point sources spread over an area of few hundreds of meters. They are enriched in olivine and serpentine making them relatively soft and susceptible for weathering. Hence, they are often found encrusted by calcrete cover or covered by alluviam or colluvial debris. Geochemically, kimberlite is diagnostically characterized by a combination of high compatible and incompatible trace element concentrations, which is often best reflected by elevated concentrations of alkalis and light rare earth elements (REE) and high field strength elements (HFSE) such as Ce, Nb, Ta and Ni (Fig.1). These elements are relatively immobile in the surface environment and can act as pathfinders for identifying proximal kimberlite sources. However, it is important to note that high concentration of Nb and other elements could be associated with felsic alkaline rocks while high Ni pulses would be possible from a variety of ultramafic rocks other than kimberlites.

Application of geochemistry in mineral exploration is known since more than fifty years now. Modern geochemistry was born in the Soviet Union in the 1930s, and the basic methodologies for regional mapping had been developed by the late 1960s, with milestone developments in the 1980s (Garrette et al., 2008). Soil is a weathering product of rocks and is one among the several sampling media that is often tested to understand the occurrence of mineralisation. Like in the case of any other mineral commodity, soil geochemistry can play a vital role in kimberlite/diamond exploration too. The important kimberlite pathfinder elements in soil include Mg, Ni, Cr, Co, Ca, Fe, Ti, Nb, Ta, REE, K, Rb, Sr, and Ba, but lithogeochemistry of the country rock versus kimberlite governs enrichment of certain elements (Gregory and Tooms, 1969; McClenaghan and Kjarsgaard, 2007). Thus, the distinct chemical composition involving trace elements may be detected in surface media over kimberlites especially even when the pipes are concealed. An examination of literature reveals that, in tropical terrains, surface geochemical prospecting is commonly executed in two ways for diamond explroation:

1. through soil or rock geochemical analyses to detect the presence of near surface or concealed kimberlite and
2. to distinguish indicator minerals using their chemistry whether significant to assess the initial ‘diamond potentiality

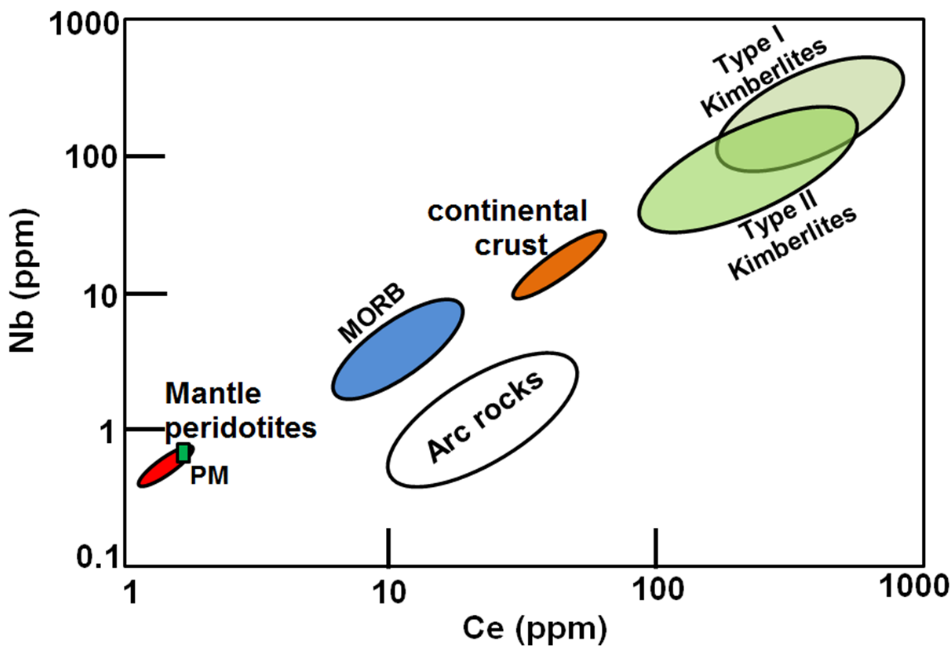

Figure 1.
Generalised geochemical characteristics of kimberlites in comparison with peridotites, oceanic basalts (MORB), continental crust, and arc rocks. Data sources primitive mantle composition (PM, McDonough & Sun 1995), MORB (Klein 2005), continental crust (Taylor & McLennan 1995), and kimberlites (Mitchell 1986).

In India, majority of the documented research work related to kimberlites provided a great knowledge in understanding the petrology, geochemistry, geochrnology and geophysics of Indian kimberlites (e.g.Akella et al., 1979; Reddy 1987, Rao et al., 1998; Anil Kumar et al., 2002; Chalapathi Rao et al., 2005; Paul et al., 2006; Anil Kumar et al., 2007; Chalapathi Rao et al., 2009; Ian et al., 2011; Joy et al., 2012; Chalapathi Rao et al.; 2014, Dongre et al.; 2014; Chalapathi Rao et al., 2016; Dongre et al., 2016; Xu et al., 2017; Shaikh et al., 2018). Despite the vast research on petrological aspects of kimberlites and lamproites, published literature pertaining to application of soil or regolith geochemistry in identifying mineral deposits in general and diamond exploration in particular, in the Indian context, is limited to a very few publications (e.g. Mathur and Alexander, 1983; Singh and Cornelius, 2005, Phani and Srinivas, 2016). In India, soil geochemistry so far has been, to some extent, used for prospecting of other mineral commodities, especially uranium (Krishnamurthy et al., 1988) and hydrocarbon (e.g. Rao, 2006; Kalpana, 2010; Rasheed et al., 2013). Also soil geochemistry has been used in environmental impact studies (e.g.Tripathy et al., 2005).

India is a vast country having about 30% of area possessing a veneer of dense forest. The significant mineral deposits are located in the Archaean and Proterozoic belts which are covered by soil with thick vegetation and are intensely weathered wherever exoposed. Hence, it is envisaged that soil geochemistry is not very effective due to presence a cover of transported material. Hence, there is perhaps an apprehension among exploration geologists that soil geochemistry may not provide useful clues in mineral exploration in the Indian geological perspective (Pujari, 2003). However, with the advent of practicing modern methods of diamond exploration, Indian geologists have also started carrying out systematic exploration for kimberlites since early 2000s. Some of the discoveries were outcome of such detailed ground exploration activities as indicator mineral surveys, stream sediment geochemistry and follow-up ground traversing (e.g. Guptasarma et al., 1986; Sravan Kumar et al., 2004; Srinivas Chowdary et al., 2007). The exploration programmes carried out by multinational companies must have comprised a large scale soil geochemical exploration for kimberlites (CRAE1, 2004, De Beers, 2004). But much of such data on pedogeochemistry applied to kimberlite search is yet to get to light. In central India, it was identified that Ni content is very much depleted in the top soil upto 2.4 m of soils over Panna kimberlite (Mathur and Alexander, 1983). Encouragingly, in the western world, utilization of soil geochemistry in kimberlite exploration received an inordinate success (e.g. Holman, 1956; Litinskii, 1963; Gregory and Tooms, 1969; Keeling et al., 2005; Fenton et al., 2006; McClenaghan and Kjarsgaard, 2007; Hamilton, 2007; CKDL, 2011, Boyer, 2013, Gura, 2017). In Congo, anamolous Ni concentrations ranging from 120-240 ppm in contrast to the background of 40 ppm was identified in sandy soil over lateritized alluvium at 2 to 7.5 m depth over a kimberlite pipe (Meneghal, 1982). Detailed surface geochemical surveys have been conducted in a variety of sampling media such as soil, plants, bogs etc. from three kimberlite fields of Moutnain lake, Buffalo Head Hills and Birch Mountains of northern Alberta (Seneshen et. al. 2005). They have noticed that elements like Ni, Co, Cu, Cr, Ti, V, Mg, Mn and Fe as 'the primary element associated' with kimberlites and Nb, Rb, Zr, Y, Sc, Th, U, Cs, REE, P, Al, K, Na, Ca, Ba, Sn, Mo, W, Cd, Zn, Pb, B, Hf, and Ga as 'the secondary element association'. Pedogeochemical surveys conducted over kimberlites in a discontinuous permafrost region in the James Bay Lowlands, southeastern Hudson Bay Lowlands have been successful in delineating REE, Y and Ni anomalies and ratios of these elements to low surface concentrations of Mn in discriminating kimberlites from other targets in sub-Arctic regions (Hattori et al., 2009). Yet another example from African countries is discovery of concealed kimberlites with the successful utilization of soil geochemistry (e.g. Daniels et al., 2012). Therefore, it is clearly evident that little or no literature is published in India, pertaining to soil geochemical surveys related to kimberlite exploration.

Owing to the difference between mineralogical and geochemical characteristics of kimberlites and the country rocks, a distinct variation is seen in the geochemical character of soils on kimberlites when compared to that of the country rock. This variation thus helps in not only defnining the surficial limits of the pipe in conjunction with geophysics but also throws light on the trace element behaviour in kimberlite and the country rock in space. Soil samples collected in *in-situ* soils will offer accurate and native geochemical results whereas those collected in drifted or transported soils will reflect the geochemical signature of their provenance elsewhere. In the early stages of development of exploration geochemistry, it was clarified that sampling and analysis of residual soil where mineralization is not masked by younger rocks or transported overburden directly reflects the sub-cropping or concealed mienralisation (Bradshaw and Thmson, 1979). Therefore, it is clearly evident that soil geochemistry can play a vital role in diamond exploration.

With this brief background, this investigation aims at identifying the anomalous elements in soils that can flash out the presence of kimberlite from a vast background of country rock especially in the Archaean granite-greenstone terrain of cratonic parts of India. This presentation stands as a first report on the behaviour of certain selected trace elements such as Nb, Cr, Ni, Co,Zr, Mg, Sr and La, in soils on diamondiferous pipes (No.s 3, 4 8 and 9) at Lattavaram kimberlite cluster (LKC) of Wajrakarur Kimberlite Field (WKF). The results of this investigation show that concentration of trace elements like Ni, Nb, Co, Cr and Mg can be used as an exploration indicator in unexplored areas in search of kimberlite pipes in the Indian craton.

2. GEOLOGICAL SET UP

The Dharwar craton is divided into two parts, Eastern Dharwar Craton and Western Dharwar Craton (EDC and WDC). The geological milieu of EDC is favourable ground for emplacement of kimberlites, lamproites and lamprophyres (e.g. Chalapathi Rao et al. 2016). The EDC hosts more than 150 kimberlite occurrences which are distributed in four distinct fields (e.g. Smith et al., 2013): (1) the diamondiferous southern Wajrakarur kimberlite field (WKF); (2) the barren northern Narayanpet kimberlite field (NKF); (3) the moderately diamondiferous central Raichur kimberlite field (RKF) and (4) Tungabhadra kimberlite field (TKF). These four fields are located towards the western margin of the Paleo-Mesoproterozoic Cuddapah sedimentary basin within a typical Archean granite-greenstone terrain comprising the Dharwar supracrustal schist belts and granitoids (Peninsular Gneissic Complex) (Fig.2). In addition, the Cuddapah Basin of Proterozoic age, has recorded more than 47 occurrences of lamproites in its northwestern and northeastern margins, distributed in five lamproite fields: Banganapalle Lamproite Field (BLF), Krishna Lamproite Field (KLF), Nallamalai Lamproite Field (NLF), Ramadugu Lamproite Field (RLF), Vattikodu Lamproite Field (VLF) and Somasila Lamproite Field (SLF) (Naqvi, 2005; Sridhar and Rau, 2005; Joy et al., 2012; Alok Kumar et al., 2013; Chalapathi Rao et al., 2014, Ahmed et al., 2016). The WKF, endowed with more than 45 kimberlite occurrences, is the largest among all kimberlite fields in its areal extent spanning over ~9500 km^2 (Das Sharma and Ramesh, 2013; Shaikh et al., 2016).

The study area, LKC is situated within the WKF (Fig.2a). The local geology of LKC area is shown in Table 1. The WKF is further subdivided into clusters of kimberlite pipes viz., Wajrakarur, Lattavaram, Anumpalli, Chigicherla, Kalyanadurgam, Timmasamudram and Gooty (Fig.2b). Majority of the kimberlites, from the WKF as well as other kimberlite fields of the EDC, so far dated are of Mesoproterozoic age of ~1100Ma and display radiogenic Sr and Nd isotopic characteristics of Group I (archetypal) kimberlites (Chalapathi Rao et al., 2004; Anil Kumar et al., 2007; Chalapathi Rao et al., 2013).

Table 1 - Geological horizons in the study area (Reddy and Suresh, 1993; Nayak and Reddy, 1996)

Kimberlites and Lamproites (1100- 1000 Ma)	
Dolerite- Gabbro Dykes (1700- 1100 Ma)	
Quartz Reefs	
Closepet Granite (2500-2400 Ma)	Pink to grey adamellite-granite suite
Intrusive Contact	
Tonalite-granodiorite – adamellite suite (2600 Ma)	Porphyritic coarse-grained tonalite, granodiorite and hornblendite granite-adamellite
Intrusive Contact	
Supracrustals (2700 Ma)	Amphibolite (Massive and schistose),chlorite schist, quartz sericiteschist, quartzite, banded magnetite quartzite (BIF)
Extrusive/Intrusive Contact	
Peninsular Gneissic Complex (PGC)	Banded tonalite-trondhjemite gneiss and migmatite with enclaves of amphibolites, talc-tremolite schist and banded magnetite quartzite/chert.

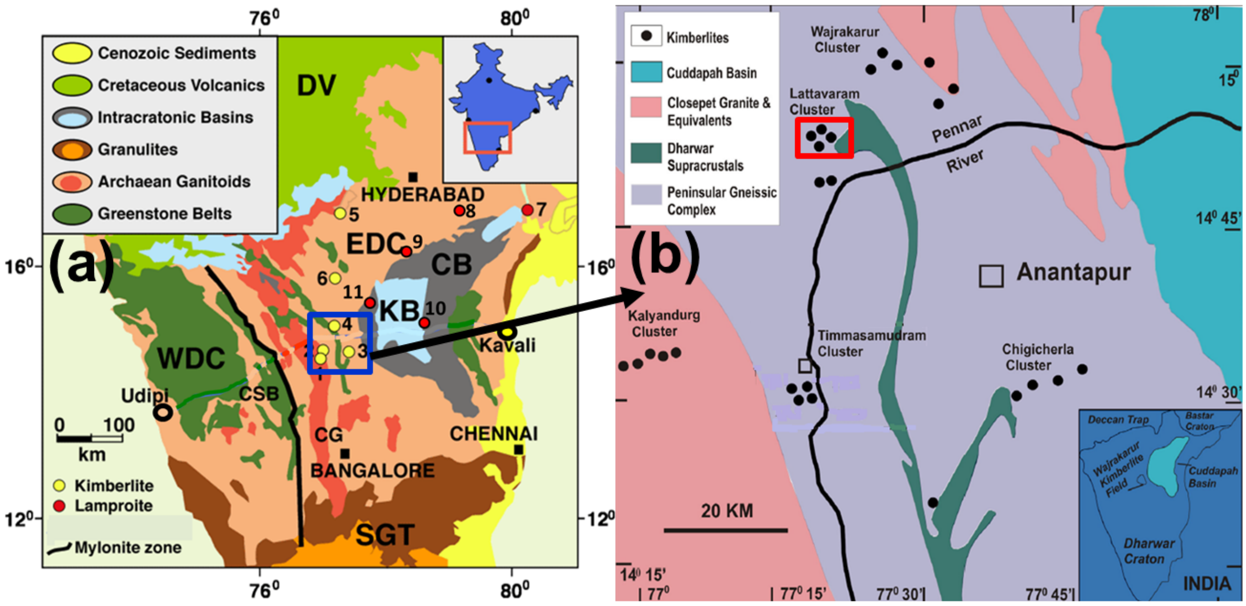

Figure 2

Generalised geology. (a) Regional geological milieu of Dharwar craton, south India showing locations of kimberlites and lamproite occurrences (modified after Griffin and O'Reilly (2004). WDC-Western Dharwar Craton, EDC-Eastern Dharwar Craton, SGT, Southern Granulite Terrain, EGGT-Eastern Ghats Granulite Terrain, CB-Cuddapah Basin, KB-Kurnool sub-Basin, DV-Deccan Volcanics, GG-Godavari Graben, CSB-Chitradurga Schist Belt and CG-Closepet Granite. Kimberlite/Lamproite clusters: 1-Kalyandurgam and Timmasamudram, 2-Brahmanapally, 3-Chigicherla, 4-Wajrakarur, Lattavaram and Anumpalli, 5-Mahabub Nagar, 6-Raichur and 7-Ramannapeta.Add 8-Vattikodu- Ramadugu, 9- Somasila, 10- Chelima and Zangamrajupalli, 11- Gooty. (b). General geological map of Wajrakarur Kimberlite Field and position of Lattavaram cluster shown in red rectangle (modified after Nayak and Kudari, 1999).

Table 2. Characteristics of Kimberlite pipes in the present study (Ravi et al., 2009).

Pipe No./ Village	Longitude/Latitude	Dimension	Area (Ha)	Diamond Incidence (cpht)	Outcrop nature	Emplacement/Host rock.
P-3 (Lattavaram)	77°17'20"E 14°55'28"N	120X40	0.48	0.28	Semi-circular	Empalced in Tonalite-Granodiorite-Adamellite (TGA) granite gneisses of Archaean age along ENE-WSW fault that displaces the Marutla Dome.
P-4 (Lattavaram)	77°17'47"E 14°55'28"N	265X130	3.45	0.25	Lobate	
P-8 (Lattavaram)	77°18'2"E 14°55'38"N	110X55	0.50	0.33	Oval	
P-9 (Lattavaram Tanda)	77°17'27"E 14°55'31"N	37X21	0.07	0.5	Circular	

The LKC pipes are distributed within an area of 1 km^2 and the four pipes are located at an average distance of 600 m to each other. The country rock granites are in general grey in color, medium grained and gneissic in nature but at the contact of kimberlite, the granites are slightly pinkish and coarse grained. The pipes are emplaced into PGC country and reported to be diamondiferous (Table.2).

Pipe-3: This diamondiferous kimberlite pipe is located 1 km E of Lattavaram village and is capped by a ~1 m thick soil. The pipe rock is only exposed as a single boulder (Fig. 3a). A large pit excavated by Geological Survey of India (GSI) can be seen wherein the soil profile distinctly shows the development of khaki-green kimberlitic calcrete duricrust. Xenoliths of lherzolite, harzburgite, dunite and eclogite are recorded from this pipe (Akella *et al.* 1979; Ganguly & Bhattacharya, 1987; Nehru & Reddy, 1989). Drilling revealed that the 'yellow ground' continues to a depth of 10 m and is underlain by 'blue ground' (Rao *et al.,* 1997). Hand specimens show a characteristic inequigranular texture imparted by olivine, occuring as macrocrysts and smaller subhedral to euhedral phenocrysts wth subordinate amounts of serpentine, spinel, perovskite, apatite, calcite and rare baddeleyite (Shaikh et al., 2018). Olivine macrocrysts are fresh relative to their groundmass counterparts, which are completely altered to serpentine. This rock may be classified as hypabyssal-facies-phlogopite-bearing macrocrystal kimberlite. Recent studies based on detailed petrography and mineral chemistry also confirmed that this is a kimberlite (Shaikh et al., 2018).

Pipe-4: Also known as the Lambadi Huts Pipe, this pipe is located 1.6 km E of Lattavaram. It is largest in size among all pipes of Lattavaram cluster and major part is covered by soil. Good outcrops are available for this pipe (Fig. 3b). Numerous float of kimberlite and kimberlitic calcrete occurs on the surface. This pipe is relatively unweathered and dark blue in colour with a few crustal xenoliths. The 'blue ground' extends to a depth of about 25 m, below which the compact '*hardébank*' extends to a depth of approximately 60 m. Drilling showed that the kimberlite-granite contact slopes at 80^o (Rao et al. 1997). This pipe is diamondiferous and is one of the least altered pipes in the Wajrakarur Kimberlite Field. Olivine is present as conspicuous and well-rounded macrocrysts and also as euhedral to subhedral serpentinised phenocrysts. The groundmass chiefly consists of phlogopite, clinopyroxene, perovskite, opaque minerals, serpentine, apatite and carbonate. Phlogopite forms laths up to 1 mm in length and also occurs as interstitial grains. Acicular laths of clinopyroxene (Cr-diopside) are fairly abundant in the groundmass. This rock is classified as hypabyssal-facies phlogopite-kimberlite. Recent studies revelaed that three distinct populations of olivine, phlogopite and clinopyroxene are recognized based on their microtextural and compositional characteristics. This pipe which was hitherto classified as kimberlite is now reclassified as lamproite (Shaikh et al., 2018).

Pipe-8: This pipe is located about 500m NE of Pipe 4, close to Lattavaram Tanda. It is concealed under calcrete cover but forms dark brown soil in comparison to the light brown soil associated with the surrounding granitic country rock (Fig.3c). At a depth of 1m, the pipe rock is hard, compact and constitutes the '*hardébank*' of the kimberlite. Bulk processing of this pipe has revealed that it is rich in indicator minerals and diamonds (Satyanarayana et al., 1992). Samples from this pipe are porphyritic and contain serpentinised pseudomorphs of olivine. Rutile inclusions are also observed in some of the phenocrysts. Olivine pseudomorphs commonly contain opaque cores mantled by carbonate minerals. It is classified as a hypabyssal-facies phlogopite kimberlite.

Pipe-9: This pipe is one of the smallest pipes of the Lattavaram cluster and is located 300 m NE of Pipe-3. Calcrete duricrust mixed with soil can be seen on the surface (Fig.3d). Drilling by the GSI revealed that the pipe rock occurs at 5 m deep where 'yellow ground' was encountered. Processed samples from test pits indicated micro-diamonds (Rao et al., 1997). This pipe rock is thoroughly altered with few relict grains preserved. This pipe is classified as a hypabyssal- facies calcite-kimberlite

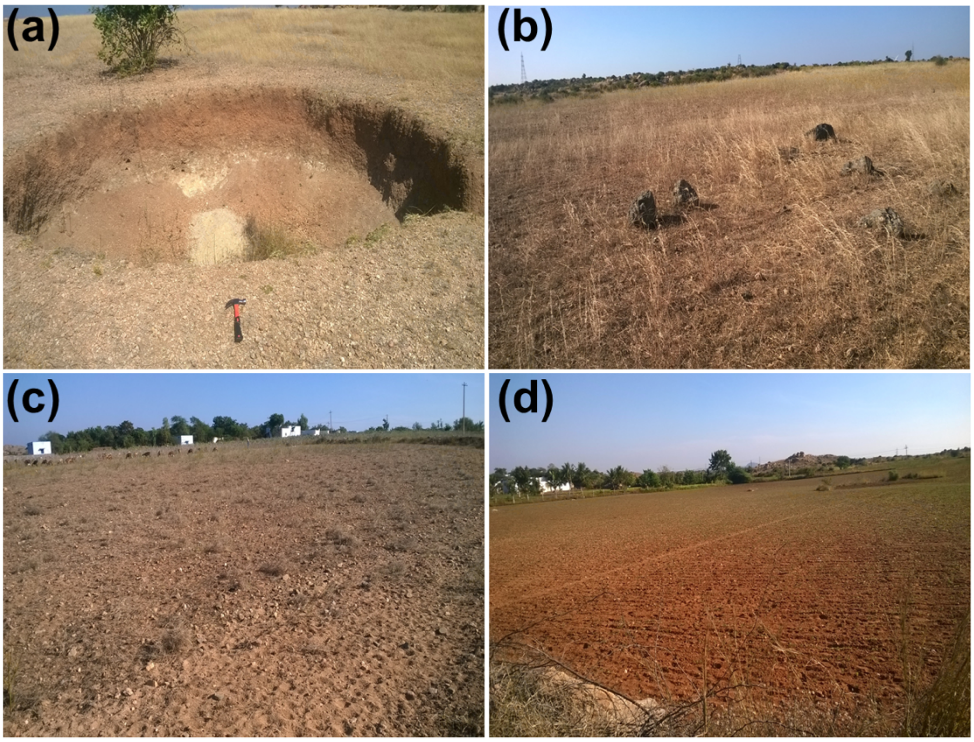

Figure 3

Field photographs showing Lattavaram pipe locations. (a) an old exploratory pit on Pipe-3. Note residual soil profile and calcrete as buff white patches. (b) outcrop boulders at pipe-4. Note extensive calcrete float. (c) Pipe-8 concealed under calcrete. (d) Pipe-9, completely covered by calcrete and colluvium

3. SAMPLING AND ANALYSES

A total 59 *in-situ* soil samples were collected on Lattavaram diamondiferous kimberlite pipes (see Table 1) at a spacing of 50 meters. The samples are collected in such a way that they cover country rock, cutting across the kimberlite pipe in N-S and EW array, using a manually operated 1 meter long auger T- rod (Fig.4a to d). The top soil of 10-20 cm was removed with the help of a spade to attenuate alluvial contamination and then the auger hole is drilled. The auger penetrated upto a depth of 80 cm to 1 m at which the sample is collected. All the samples are collected in the same soil horizon. After collecting the sample, the hole was rehabilitated by filling the soil material back (Fig.4e). The soil sample is generally moist; hence the entire sample was air dried, gently crushed and pulverized to powder and sieved to 80# mesh (177 microns). The sample then coned and quartered. About 250 gm of sample was packed in paper bags and sent to an NABL (National Accreditation Board for Testing and Calibration Laboratories, Government of India, Gurgaon, New Delhi) accredited laboratory at Bangalore well-versed in geochemical analysis of kimberlties. The samples were subjected to four acid digestion (HF-hydrofluoric acid, $HClO_4$-perchloric acid and HCl-hydrochloric acid, HNO_3- nitric acid and made up with Milli-Q water). At first, the samples were digested in nitric and perchloric acids followed by HF and HCl, so that the entire sample gets thoroughly digested. The sample then subjected to ICPOES (Agilent 725ES) and ICPMS (Agilent 7700x) deploying IC587 and MS587 methods for anlysis of trace elements viz., Nb, Cr, Ni, Co,Zr, Mg, Sr and La. Quality control of geochemical analysis was achieved through incorporating repeated samples, blanks and testing with internationally approved standard reference materials. Some part of the soil samples was sieved through 2mm mesh and washed with water to remove clay content. The -2mm to +0.5 mm portion was washed in 20% H_2O_2 (hydrogen peroxide), 20% HCl and distilled water. The sample then subjected to magnetic separation and the rest of the sample is processed for obtaining heavy mineral (HM) concentrate using a manually operated jig. The jigging was repeated until all the HM portion is separated. The HM concentrate thus separated is further subjected to heavy dense media separation using bromoform ($CHBr_3$, Specific gravity 2.89) to obtain kimberlite indicator minerals (KIMs) which is observed and picked under a stereomicroscope

4. RESULTS AND DISCUSSION

Interpretation of the geochemical results focuses on certain key elements that are useful for identification of kimberlite, which are relatively immobile in the surface environment. The elements that have migrated due to soil forming process may be derived from two sources i.e., from an endogeneic or exogenic source. Elements from an endogeneic source are derived from primary minerals, which are known as bound elements (Bradshaw et al., 1974; Leinz et al., 1993). The selected elements Nb, Cr, Ni, Co,Zr, Mg, Sr and La are considered as bound elements due to their origin in the C-horizon from the parent kimberlite rock due to weathering and buyoyancy which are concentrated in the B-horizon in the event of low rainfall and infiltration (Mann et al., 1995; Mann et al., 1997). During the physical examination of HM concentrate of soils analysed in this study, microscopic grains of kimberlitic indicator minerals (KIMs) such as pyrope, Cr-diopside, ilmenite, picroilmenite, olivine and chromite are observed (Fig. 5). A summary of various statistical parameters calculated for trace elements in granitic and kimberlitic soils of the present study are presented in Table 3 and 4

The elemental concentrations are plotted in histograms for Nb, Cr, Ni, Co, Zr, Mg, Sr and La (Fig. 6 to 12). The moving average value has been used to draw a line across concentration levels of each element (red line in Fig.6 to 12). The average concentrations of trace elements in each pipe have been normalized with those of Upper Continental Crust (UCC) of Taylor and McLennan (1964). The pipe-4 displays higher concentration of Cr, Ni, Co, Mg and Sr (Fig. 6-13 (h)). The pipe-8 shows higher content of Nb and lower content of Cr, Co and Mg. The pipe-9 soils show a low concentration of Nb (Fig.6h), Ni (Fig.8h), Mg (Fig.11h) and La (Fig.13h) and a high pulse in the concentration of Zr (Fig.10h). It should be noted that, when compared to other three pipes in the LKC, pipe-3 shows insignificant variations in UCC normalised trace element abundances, which might be due to intense weathering that might have contributed to less preservance of KIMs within the pipe-3 soils. The higher concetrations of elements like Nb, Ni, Zr, Mg, Co observed within the soils is attributed to the presence of KIMs. The higher concentration of Ni is attributed to presence of greenish clayey soil enriched in highly serpentinised olivine. On an average, the LKC pipes show a minimum of 45 ppm of Nb concentrations when compared with the background soils (Table 3). Therefore it can be considered as threshold value to test the target initially. The granitic soils obviously have less concetrations of the analysed trace elements owing to the absence of such minerals in the soils as they are produced from granites or gneisses. However, zircon content has a close difference in soils of both kimberlites and granites. Presence of accessory zircon in granitic country rocks is preluded to be the reason for this. Yet another element, La shows no anamolous difference in its concentration between soils of kimberlitic and granitic origin (Fig.10).

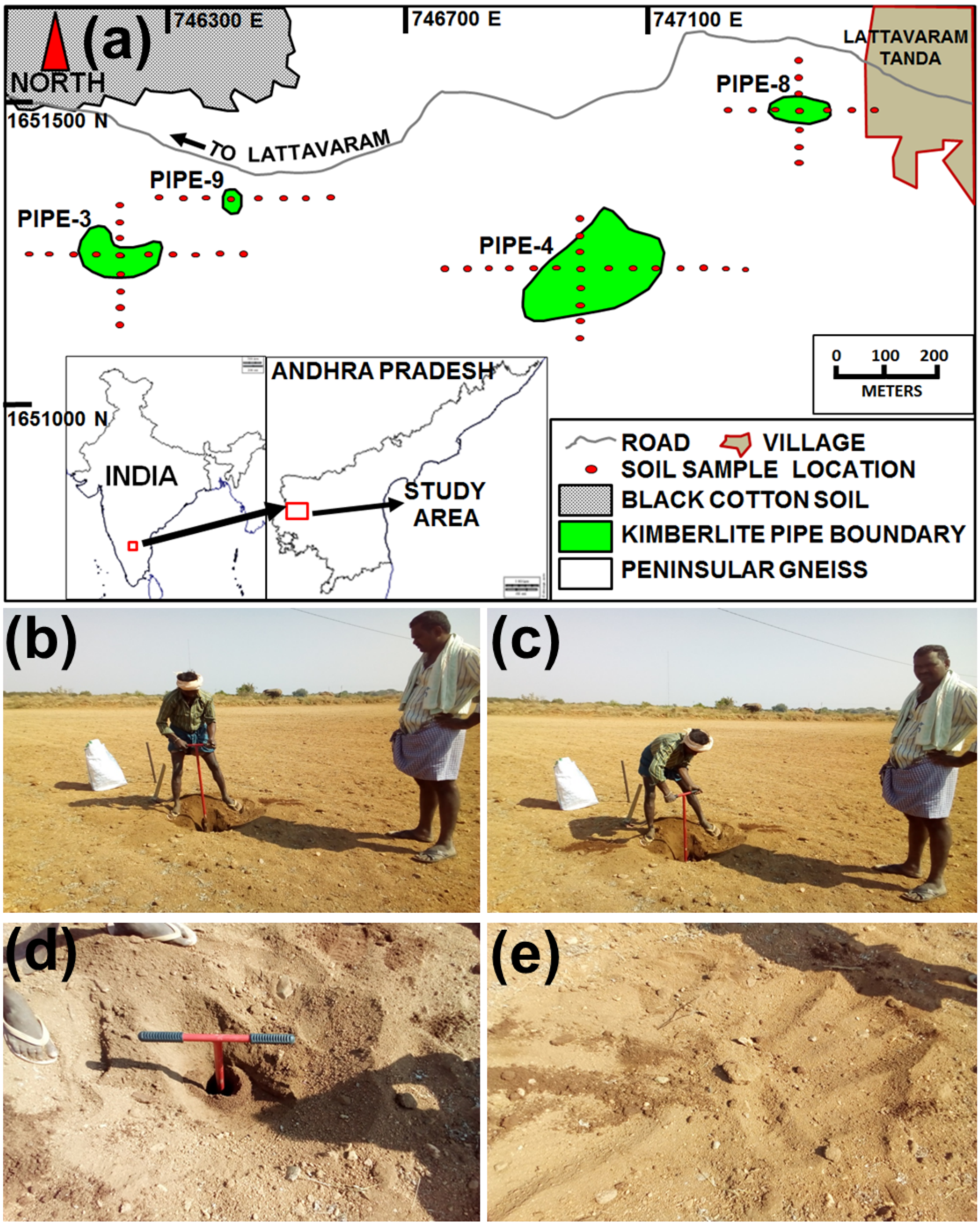

Figure 4
Sampling plan in the present study. (a) Kimberlite pipe boundaries in Lattavaram cluster (Ravi et al., 2009), showing soil sample traverse. (b), (c) and (d) Auger sampling using T-rod. (e) rehabilitated auger hole.

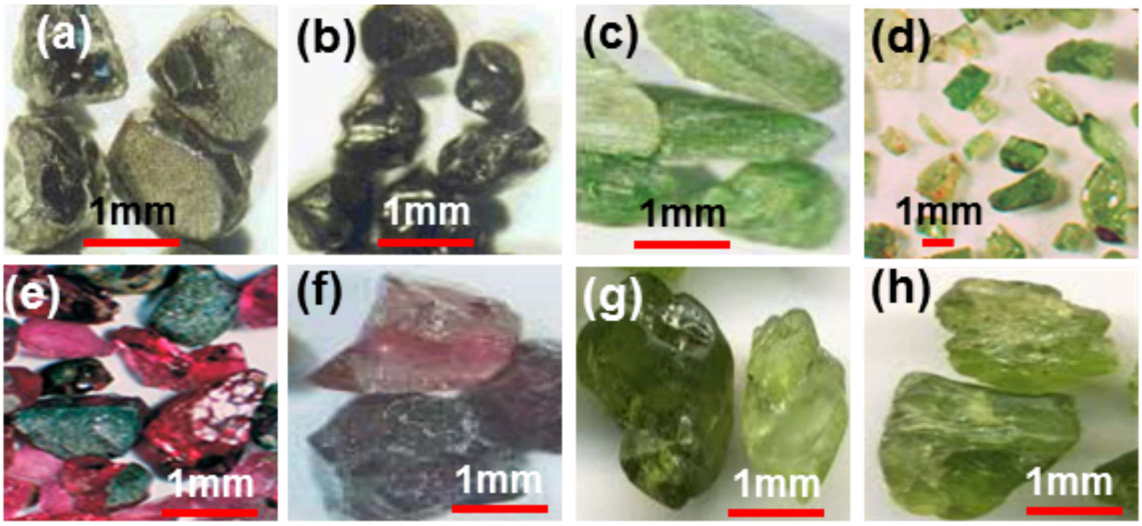

Figure 5
Kimberlite indicator minerals (KIMs) in *in-situ* soils of Lattavaram. (a) picroilmenite (b) chrome spinel (c) and (d) chrome diopside (e) and (f) pyrope garnet (g) and (h) olivine. Photographs captured using stereo microscope

Table 3. Statistical parameters in trace element concentrations in soils of Lattavaram kimberlite pipes. G- Granitic soil, K- Kimberlitic soil.

ELEMENT (ppm)		Nb		Ni		La		Zr	
PIPE	**SOIL TYPE**	**G**	**K**	**G**	**K**	**G**	**K**	**G**	**K**
Pipe-3	**Minimum**	9	54.5	11	280	33.5	63.2	64	102
	Maximum	21.5	73	25.5	320	55.25	69.65	111	123
	Average	14.47	64.55	19.1	302.75	44.25	65.54	87.62	113
	Median	12.3	65.34	21	305.5	45.43	64.66	89	113.5
	Std.Dev.	4.51	7.69	4.7	17.23	5.29	2.97	15.15	8.68
Pipe-4	**Minimum**	5.5	46.67	107	650	38.79	53.7	63.26	90
	Maximum	9.32	62.34	150	843.23	56.73	66.45	89.23	115.74
	Average	7.29	52.46	124	728.35	45.42	60.82	74.90	107.15
	Median	7.15	50	121	683	44.17	61.24	73.89	109.56
	Std.Dev.	1.08	5.35	13.3	78.80	5.50	3.90	7.38	7.72
Pipe-8	**Minimum**	3.2	128.4	43.3	134.5	42.35	55.64	59.8	112.12
	Maximum	8.32	182	58.7	193.43	55.27	63.24	82.4	121.3
	Average	6.17	145.9	47.2	161.35	48.19	59.85	72.10	115.32
	Median	6.76	136.5	45.8	158.73	47.8	60.26	73.54	113.94
	Std.Dev.	1.83	24.8	4.73	24.524	4.20	3.32	8.26	4.28
Pipe-9	**Minimum**	3.5		14.5		12.34		121.35	
	Maximum	8.5		21.3		18.8		155.5	
	Average	5.85	56.7	18	118.67	16.00	31.5	142.12	160.45
	Median	5.6		17.7		16.3		143.22	
	Std.Dev.	1.87		2.13		2.078		12.34	

Table 4. Statistical parameters in trace element concentrations in soils of Lattavaram kimberlite pipes. G- Granitic soil, K- Kimberlitic soil.

ELEMENT (ppm)		Cr		Mg		Co		Sr	
PIPE	SOIL TYPE	G	K	G	K	G	K	G	K
Pipe-3	Minimum	33	341	4237	13664	6	29	98	235
	Maximum	111	412	9250	31700	18	34	155	301
	Average	58.43	375.8	6536.8	23091	11.162	31.5	122.01	269
	Median	58	375	6452	23500	11	31.5	119	270
	Std.Dev.	19.66	29.28	1410.8	7575	4.1392	2.082	16.626	28.18
Pipe-4	Minimum	32.5	341.9	1897	48900	6.12	41.45	176	212.4
	Maximum	56.7	401.2	6523	63000	12.2	55.32	213.5	411.4
	Average	40.54	380.6	3680.3	55171	8.7708	45.34	197.07	362.1
	Median	40.1	383.6	3780.5	53843	8.58	43.67	195.02	380.3
	Std.Dev.	7.274	16.92	1417.6	4531	1.6057	4.345	10.872	59.31
Pipe-8	Minimum	90.44	98.55	1063	3898	7.76	8.5	211.5	321
	Maximum	101.2	116.3	2104	6126	11.26	12	278	335
	Average	95.55	110.7	1396.9	5302	9.2067	10.54	252.55	328.9
	Median	96.4	113.9	1324	5592	8.3	10.83	265.4	329.8
	Std.Dev.	3.397	8.232	337.61	969.8	1.4371	1.553	26.222	6.235
Pipe-9	Minimum	5.78		980		7		167.78	
	Maximum	9.2		1663		16.7		188.5	
	Average	7.993	189	1262	5451	11.503	32	178.12	345
	Median	8.3		1231		11.28		178.94	
	Std.Dev.	1.079		229.89		3.1158		6.576	

5. CONCLUSIONS

Strong geochemical signals of trace elements in *in-situ* soils of Lattavaram kimberlite pipes (pipes-3, 4, 8 and 9) are encouraging, considering that the kimberlite outcrops are weathered and overlain by calcrete and colluvium. The kimberlitic soils show conspicuous enrichment of elements like Nb, Cr, Ni, Co,Zr, Mg, Sr and La than in the *in-situ* soils on country rock granites. The enrichment of these elements in the soils is attributed to the presence of kimberlitic indicator minerals like olivine, pyrope, Cr-diopside, ilmenite etc., well preserved in the *in-situ* soils in the area. When compared to the background soils, the kimberlitic soils contain a threshold concentration of 45 ppm, which can be considered as a guide to prioritise the target for further exploration. From this study, it can be envisioned that trace element pedogeochemistry, in areas covered with residual soil, can play a significant role and serve as an effective sampling medium offering a distinct geochemical behaviour when compared to background, thereby guiding in identifying kimberlite pipes. It can also be envisaged that, in case of unexplored prospects, the residual soil samples have to be collected along a traverse over a target covering the background and also the kimberlite lithology, using a shorter sampling distance of ~25 to 50 m. The traverse should be designed to collect similar surface media under similar surface conditions and topography. The soil geochemical survey area must be chosen by indicator mineral results and ground geophysics traverse which needs to be eventually followed up by pitting or drilling to confirm the occurrence of kimberlite pipes.

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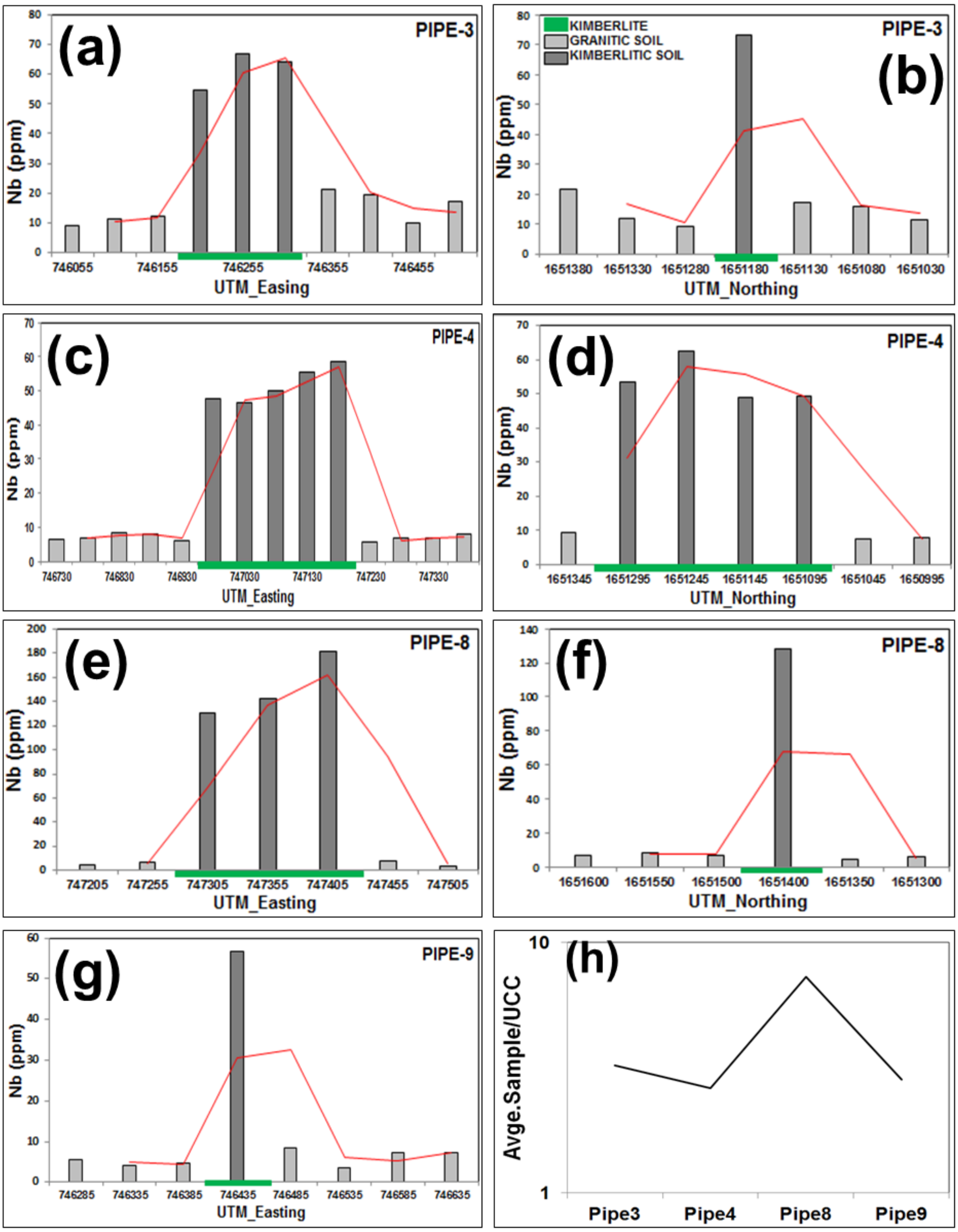

Figure 6.
Trends in concentrations of Nb in residual soils on Lattaavram pipes.

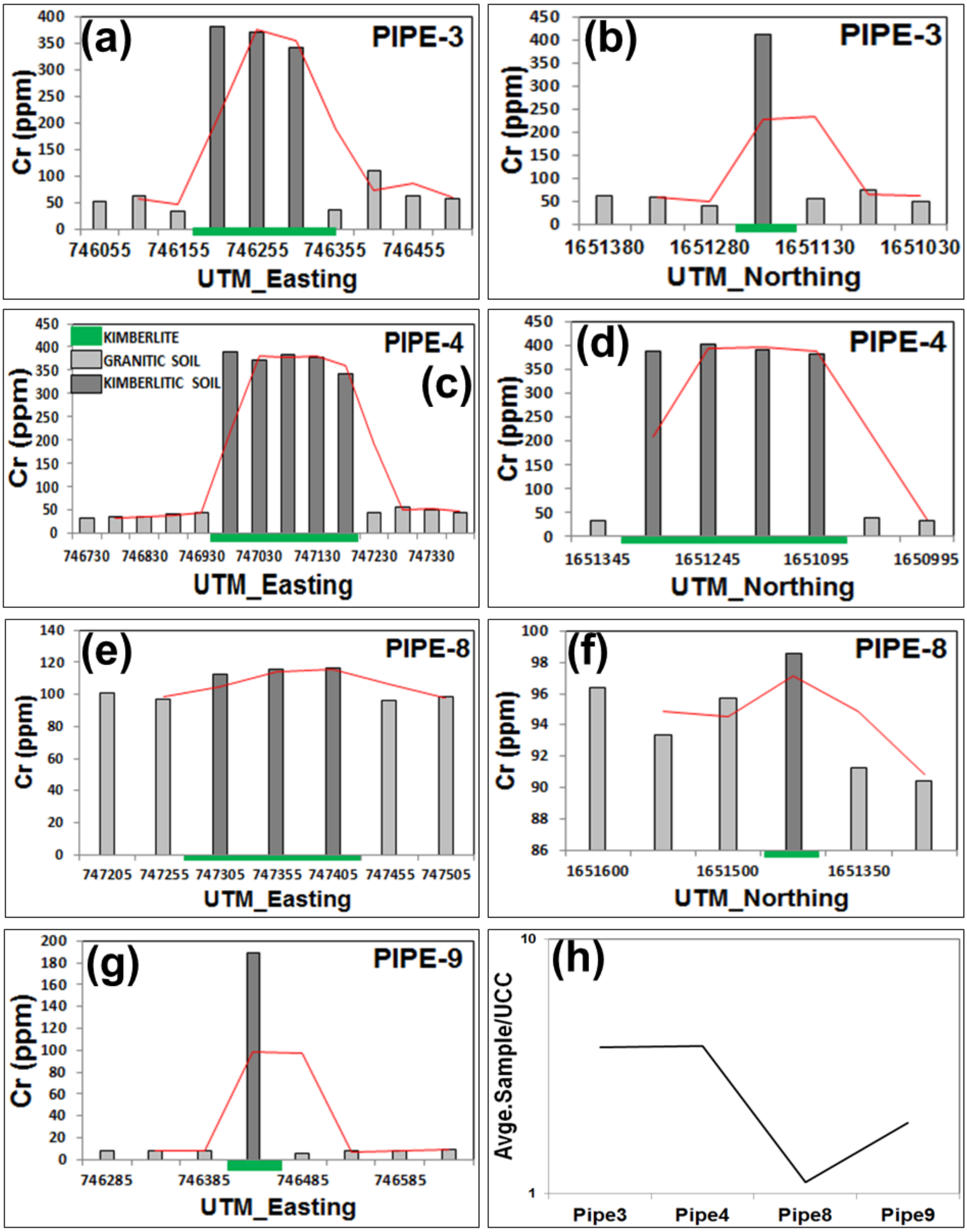

Figure 7.
Trends in concentrations of Cr in residual soils on Lattaavram pipes

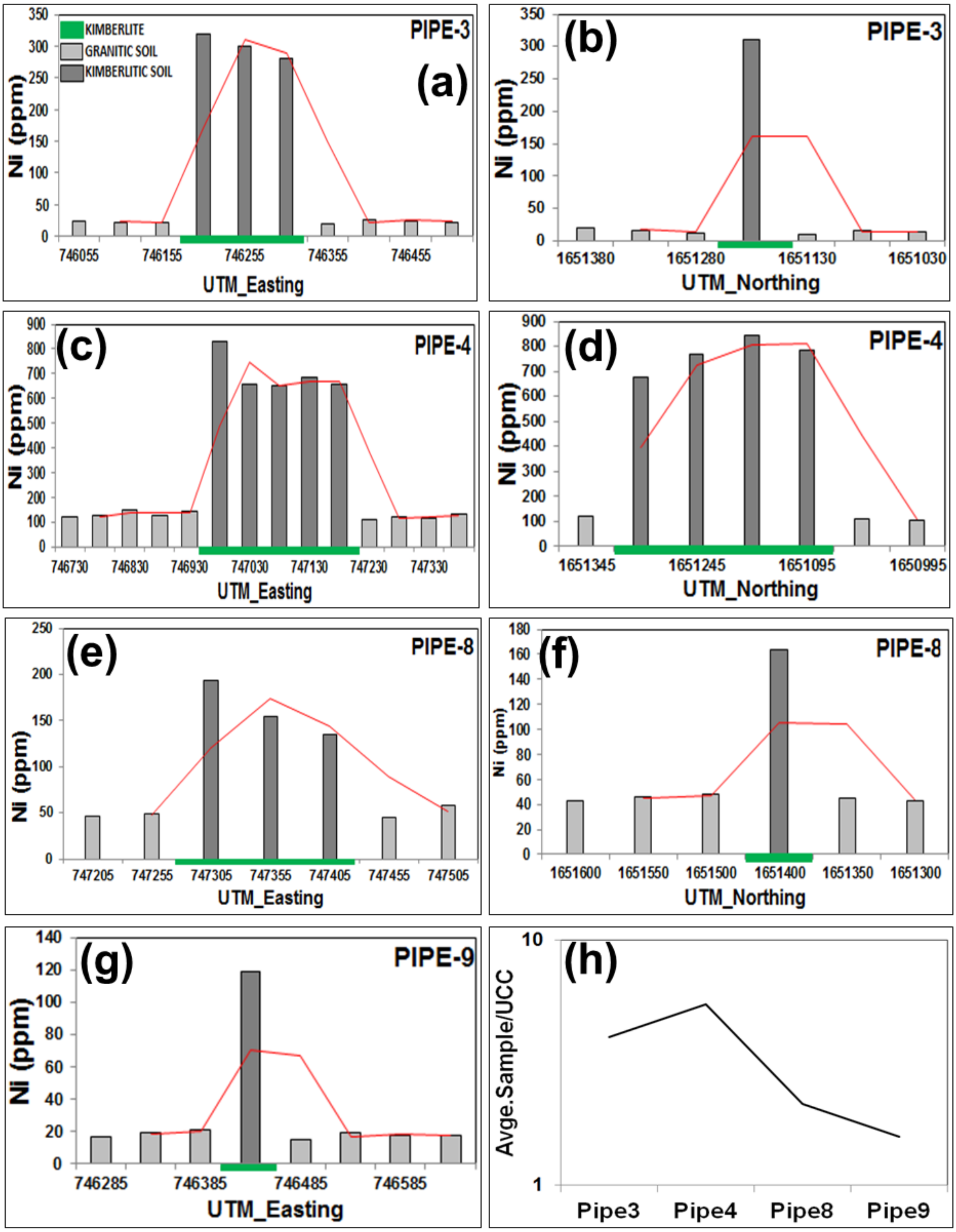

Figure8.
Trends in concentrations of Ni in residual soils on Lattaavram pipes

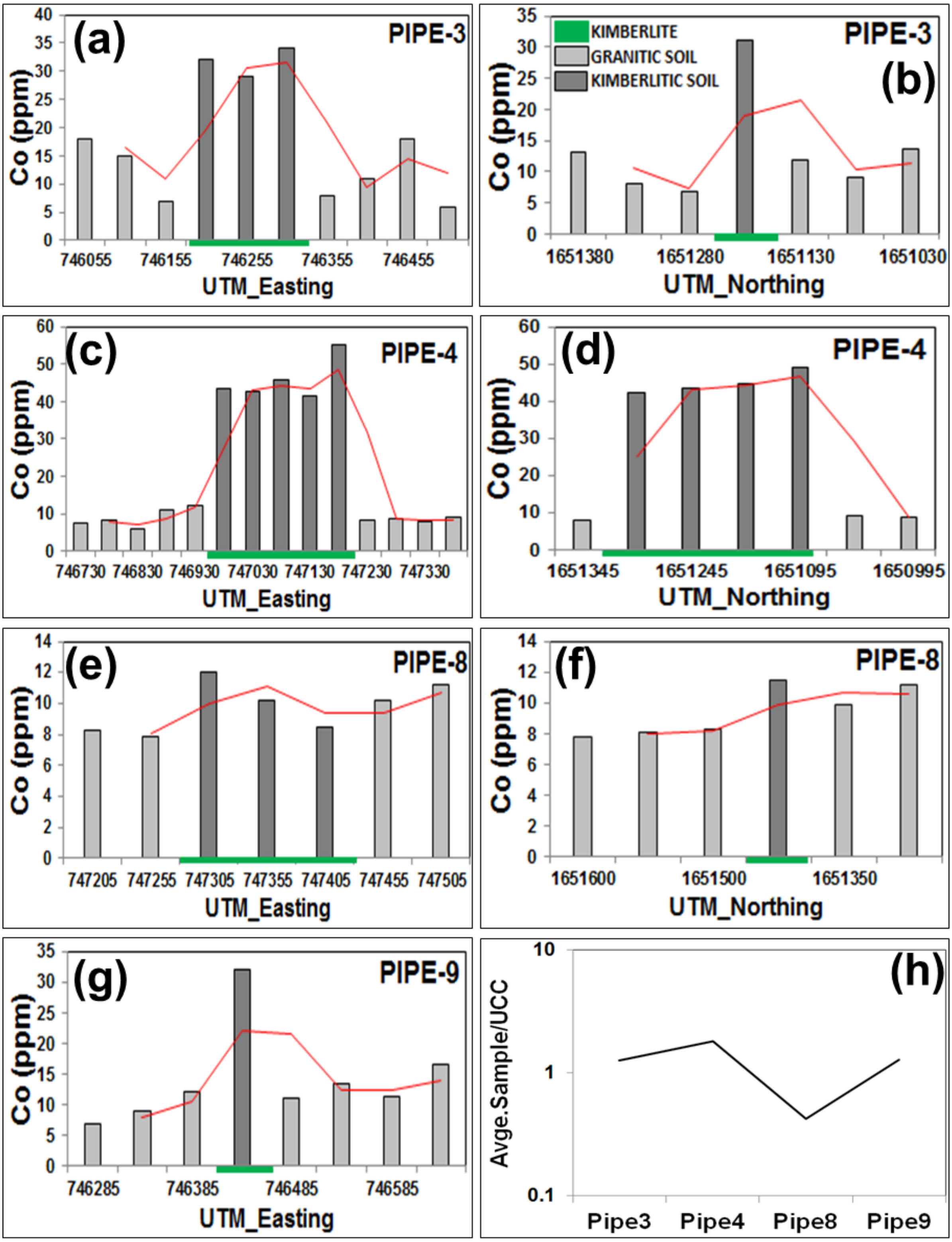

Figure 9.
Trends in concentrations of Co in residual soils on Lattaavram pipes

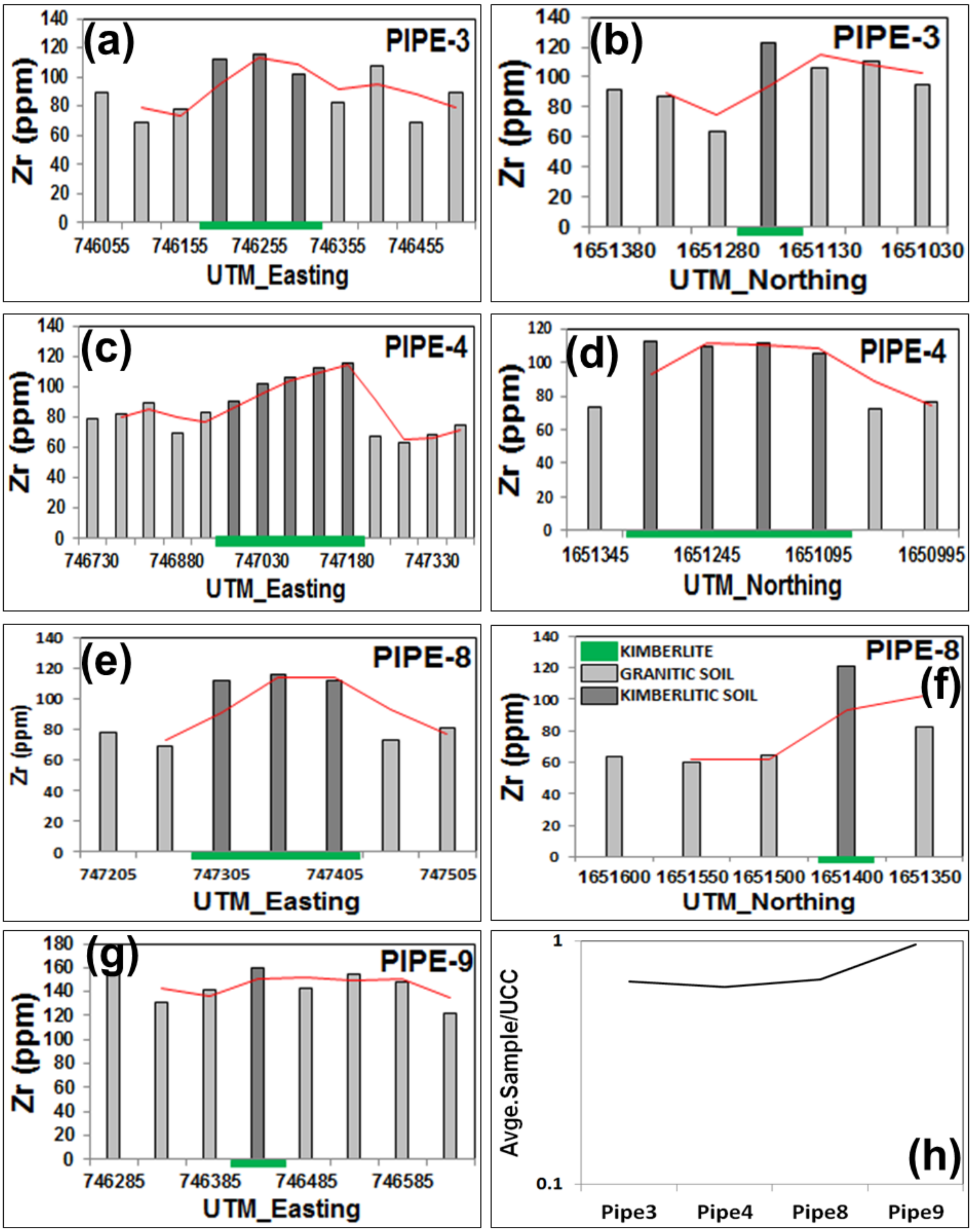

Figure 10.
Trends in concentrations of Zr in residual soils on Lattaavram pipes

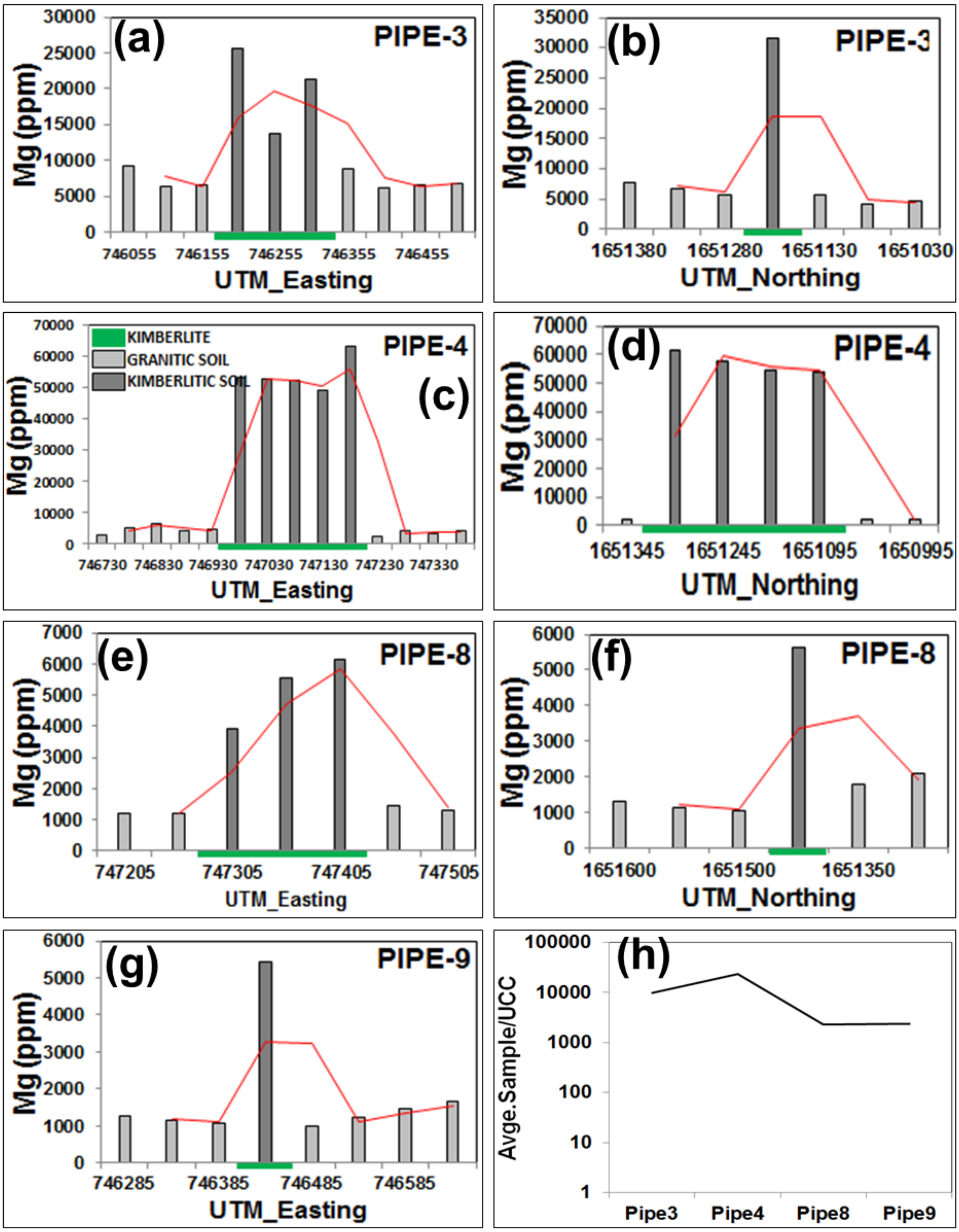

Figure 11.
Trends in concentrations of Mg in residual soils on Lattaavram pipes.

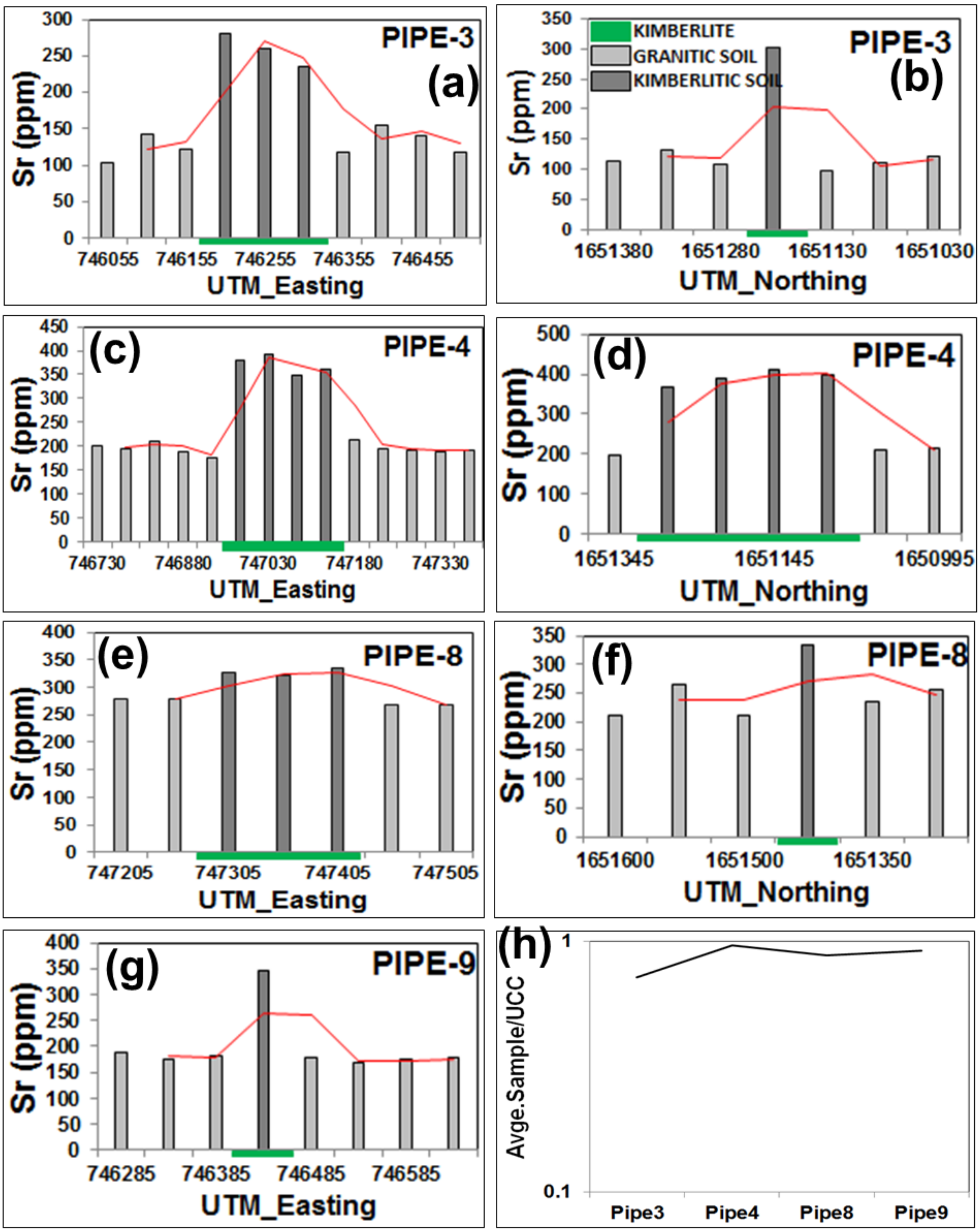

Figure 12.
Trends in concentrations of Sr in residual soils on Lattaavram pipes

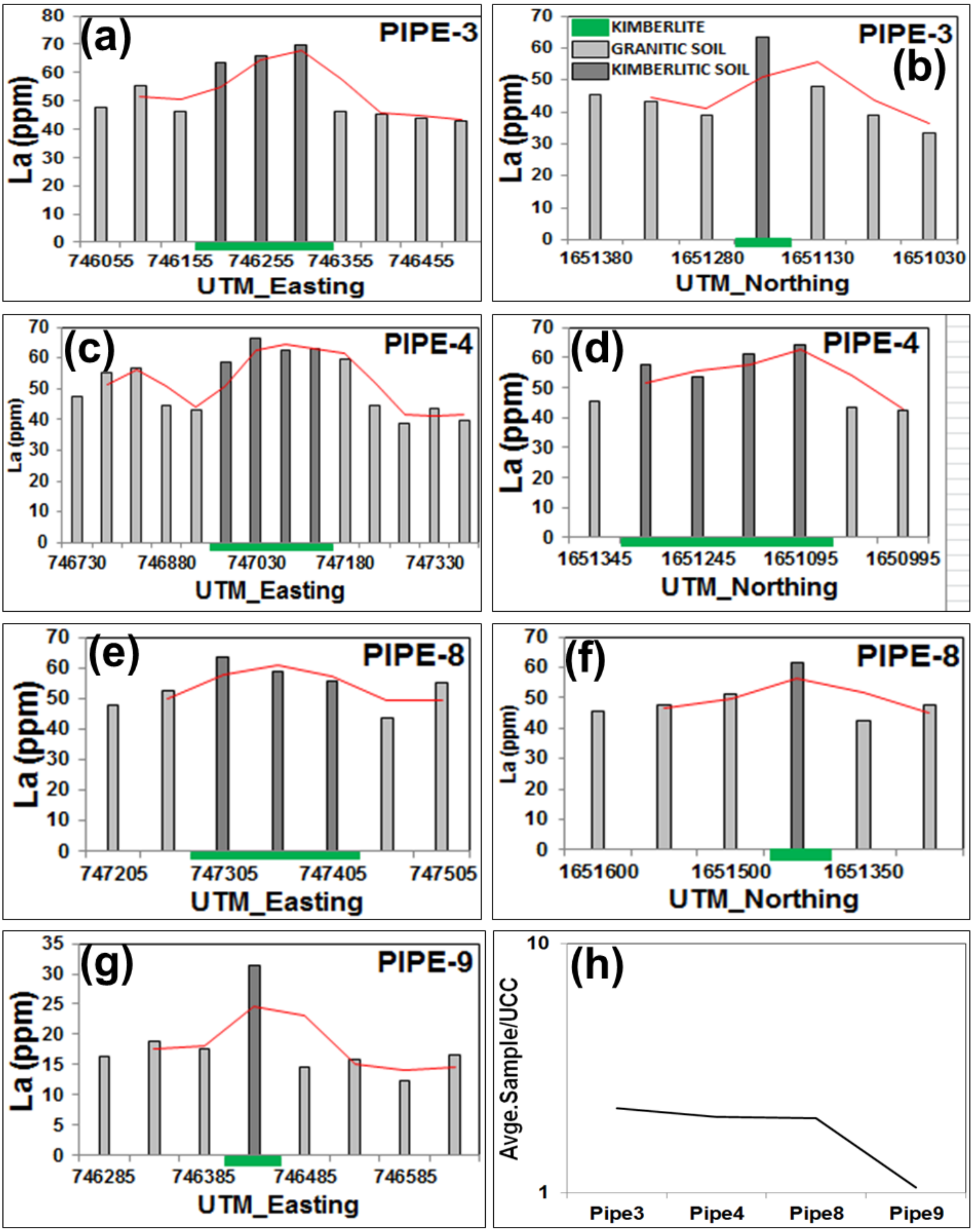

Figure 13
Trends in concentrations of La in residual soils on Lattaavram pipes

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