change with distance from the mouth. During dry season, velocities at the head of the estuary were negligible compared to those at the mouth of the estuary. Thus average current speeds during flood and ebb tides are similar and vary from 0.02 to 0.6 m s^{-1}. Across Yanam (marked in box in Figure 1), the model-generated average flood and ebb currents were 0.18 and 0.22 m s^{-1} respectively, which are close to observations (0.16 and 0.20 m s^{-1}).

The estuary was vertically well mixed in terms of density stratification during the dry season due to less run-off compared to tidal prism. It is therefore sufficient to use the TIDAL model for the present case, since the vertical approximations associated with averaging are likely to be small. Model results reveal that majority of the flow was found to be along the channel axis (i.e. high iso-bath contour). During floods, flow is the southwest direction and it changes to northeast direction during ebb period, which indicates that the model results resemble flow in the real estuarine system. However, secondary baroclinic flows, which are often generated in estuaries (although shallow depths ensure a vertically mixed water column for the present case studies), will not be simulated in a depth-averaged model and, therefore, 3D modelling will be required. Further, the model was run for a grid size of 100 m. Increasing the grid resolution and data from small tributaries further improve the accuracy of the simulations. The value of roughness length (K) is suggested as 0.085 m, which is about eight times higher than that used earlier by the modellers[12,22]. Using the above value, incorporating the freshwater discharge from the small tributaries and increasing the grid resolution (50 m × 50 m) may further improve the model results.

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Occurrence of rare titanium–niobium-rich astrophyllite in the Podili alkali granite pluton, Prakasam district, Andhra Pradesh, India

Close to the eastern margin of the Proterozoic Cuddapah basin[1,2] and to the south of Podili, a crudely foliated alkali granite pluton occupying an area of 10 sq. km is emplaced within the metavolcano–metasedimentary sequence of the Archaean Nellore schist belt (NSB). In its western part, the 'Podili alkali granite pluton' exhibits sharp contact with N–S to NNE–SSW-trending quartz–chlorite schist and quartzite of NSB (Figure 1). Enclaves of NSB lithounits are noticed in the pluton. The Podili pluton is traversed by a semi-elliptical syenite, dykes of alkali feldspar granite and tourmaline-bearing quartz veins. Astrophyllite–arfvedsonite-bearing alkali granite is localized along the western part of the Podili pluton[3]. It is coarse-grained, leucocratic in appearance and shows N–S banding.

Table 1. Composition of astrophyllite, arfvedsonite, plagioclase and K-feldspar from alkali granite of the Podili pluton, Prakasam district, Andhra Pradesh, India

	Astrophyllite				
Oxides	Niobokuplestkite	Kuplestkite	Arfvedsonite	Plagioclase (albite)	K-feldspar
Sample no. KG-208					
SiO_2	36.32	35.17	50.07	69.72	64.43
TiO_2	10.89	7.52	0.20	0.03	0.00
Al_2O_3	0.79	1.25	1.15	19.24	17.97
Cr_2O_3	0.01	0.02	0.005	0.00	0.00
Fe_2O_3	3.05	3.57	4.67	0.00	0.12
FeO	33.91	33.44	33.21	0.41	0.00
MnO	1.42	1.47	0.60	0.01	0.04
MgO	0.00	0.04	0.155	0.01	0.00
CaO	0.08	0.05	0.025	0.00	0.00
Na_2O	2.44	2.31	7.92	11.64	0.23
K_2O	6.17	6.71	1.39	0.02	18.27
NiO	0.00	0.07	0.00	0.00	0.04
Nb_2O_5	1.30	6.04	NA	NA	NA
ZrO_2	0.21	0.30	NA	NA	NA
Total	96.60	97.97	99.42	101.08	100.10
Cations on the basis:	29 Oxygens	29 Oxygens	23 Oxygens	8 Oxygens	8 Oxygens
Si	8.0097	7.7891	7.9494	3.0122	2.9960
Ti	1.8061	1.2525	0.2385	0.0010	0.0000
Al	0.2054	0.3263	0.2152	0.9798	0.9699
Cr	0.0017	0.0035	0.0000	0.0000	0.0000
Fe^{+3}	0.5065	0.5957	0.5586	0.0000	0.0041
Fe^{+2}	6.2548	6.1945	4.4098	0.0148	0.0000
Mn	0.2653	0.2758	0.0807	0.0004	0.0016
Mg	0.0000	0.0132	0.0367	0.0006	0.0000
Ca	0.0189	0.0119	0.0042	0.0000	0.0000
Na	1.0434	0.9920	2.4394	0.9751	0.0204
K	1.7359	1.8959	0.2815	0.0011	1.0673
Ni	0.0000	0.0125	0.0000	0.0000	0.0015
Nb	0.1296	0.6048	NA	NA	NA
Zr	0.0226	0.0324	NA	NA	NA
Molecular proportions of end-members:	–	–	–	Or–0.11 Ab–99.89 An–0.00	Or–98.12 Ab–1.88 An–0.00

The occurrence of the Podili alkali granite and Kanigiri biotite granite to the south of Podili was recorded much earlier (D. Vasudevan and T. M. Rao, unpublished; A. D. Prasada Rao and A. D. Ahluwalia, unpublished). Petrological studies on Kanigiri–Podili granites[4] (N. Nagaraja Rao, unpublished) indicated the occurrence of fluorite, zircon, sphene, garnet, clinozoisite, apatite, topaz and columbite as accessory minerals along with molybdenite, arsenopyrite, pyrite and discrete grains of samarskite, fergusonite and monazite in the Kanigiri granite (1120 ± 25 Ma)[5]. Trace element geochemistry indicated that both the Podili and Kanigiri granites exhibit characteristics of within-plate granites[6].

Detailed petrographic and mineral chemistry studies brought to light the occurrence of 'Astrophyllite', a hydrous potassium iron titanium silicate (triclinic, $(Na,K)_3(Fe^{+2},Fe^{+3},Mn)5\ Ti_2Si_8O_{24}(O,OH,F)7$), along the sheared western contact of the Podili alkali granite. Astrophyllite, with d(A°) values of 10.58, 3.51 and 2.77 was identified by XRD studies[7].

Chemical composition of both astrophyllite and arfvedsonite (Table 1) was determined using a JEOL EPMA model: JXA 8600 MX Super probe (WDS). Operating conditions were: accelerating voltage, 15 kV; probe current, 1×10^{-8} A; counting time 10 sec; background counting time, 5 sec; correction procedure, Bence & Albee (BAA); standards used, natural/synthetic compounds supplied by M/s. JEOL Limited, Japan, and ASTIMAX, Australia. Electron probe microanalyses revealed that the bluish alkali amphibole with Si – 7.9494, (Na + K) – 2.7209 and Mg/Mg + Fe^{2+} – 0.008, falls in the field of arfvedsonite[8].

Petrographic studies and determination of modal composition revealed that the arfvedsonite–astrophyllite alkali granite is essentially composed of microcline microperthite (38.8%), quartz (44.5), plagioclase (4.7), astrophyllite (1.7%), arfvedsonite (4.8%) and biotite (3.2%), whereas zircon, allanite, titanite, fluorite and opaques are observed as accessory minerals. Modal analyses data revealed that the rock is alkali feldspar granite[9]. The hypersolvus nature of astrophyllite–arfvedsonite-bearing alkali granite is evident by the predominance of K-feldspar perthite and absence of plagioclase as discrete phase[10]. Astrophyllite is flaky in habit with high-surface relief,

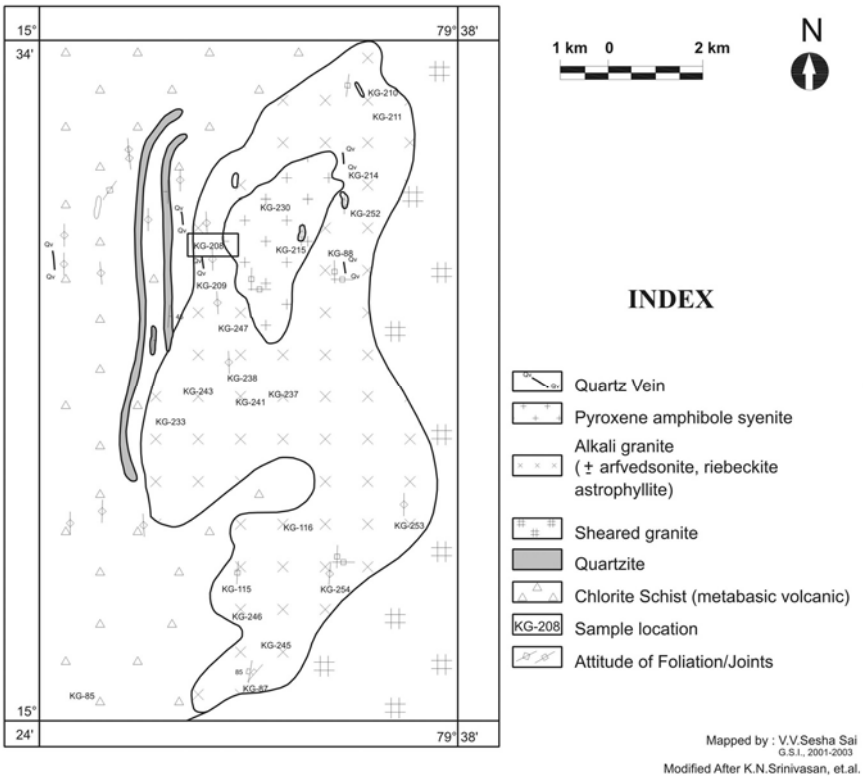

Figure 1. Geological map of the Podili alkali granite pluton, Nellore schist belt, Andhra Pradesh, India.

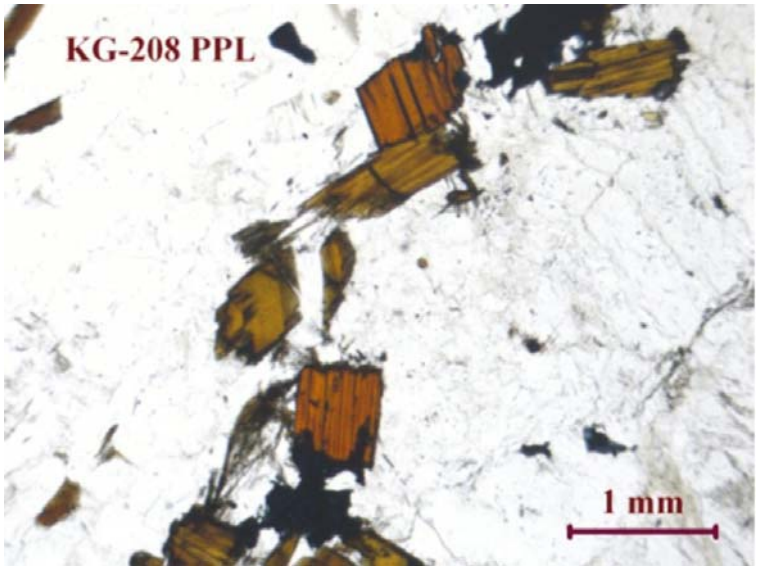

Figure 2. Photomicrograph showing orangish-red to yellowish-brown pleochroism in astrophyllite. Note one set of prominent cleavage and flaky nature of astrophyllite.

one set of prominent cleavage, pleochroic in shades of orange-brown to yellowish-brown (Figure 2) and shows positive sign of elongation, whereas arfvedsonite is pleochroic atypically in shades of indigo-blue to dark grayish-blue. Some grains of astrophyllite exhibit zoning under crossed nicols (Figure 3). Quartz is recrystallized and sub-grains exhibit progressive extinction. Fine-grained admixture of quartzo-feldspathic material with phyllosilicates is often noticed occupying the interspaces between larger distorted and fragmented K-feldspar microperthite grains indicating that the rock is deformed in ductile domains. Plagioclase ($Ab_{99.89\%}$, Table 1) occurs mostly as fresh patches in partially sericitized microperthite grains.

Chemical composition of astrophyllite grains determined by electron microprobe revealed variation in Nb_2O_5 and TiO_2 contents. Titanium-enriched grain with TiO_2 (10.89%) and Nb_2O_5 (1.30%) is close to niobokupletskite[11] composition with calculated structural formula $(K_{1.73}Na_{1.04})\Sigma = 2.79$ $(Fe_{6.76}Mn_{0.26})\Sigma = 7.02$ $(Ti_{1.81}Nb_{0.13}Zr_{0.02})\Sigma = 1.96$ $Si_{8.00}$, while the niobium enriched grain with Nb_2O_5 (6.04%) and TiO_2 (7.52%) is close to kupletskite in composition with calculated structural formula $(K_{1.89}Na_{0.99})\Sigma = 2.88(Mn_{0.27}Fe_{6.78})\Sigma = 7.05(Ti_{1.25}Nb_{0.60})\Sigma = 1.85Si_{7.79}$; the chemical composition data suggest solid solution relation between niobokuplestkite and kuplestkite, both belonging to astrophyllite group of minerals. Coupled substitution between Ti^{4+} and Nb^{5+} between niobokupletskite and kupletskite is extensively noticed in astrophyllite-bearing nepheline syenite from Mont Saint-Hilaire, Quebec, Canada[11].

Astrophyllite occurs in nepheline syenites, alkali granites and associated

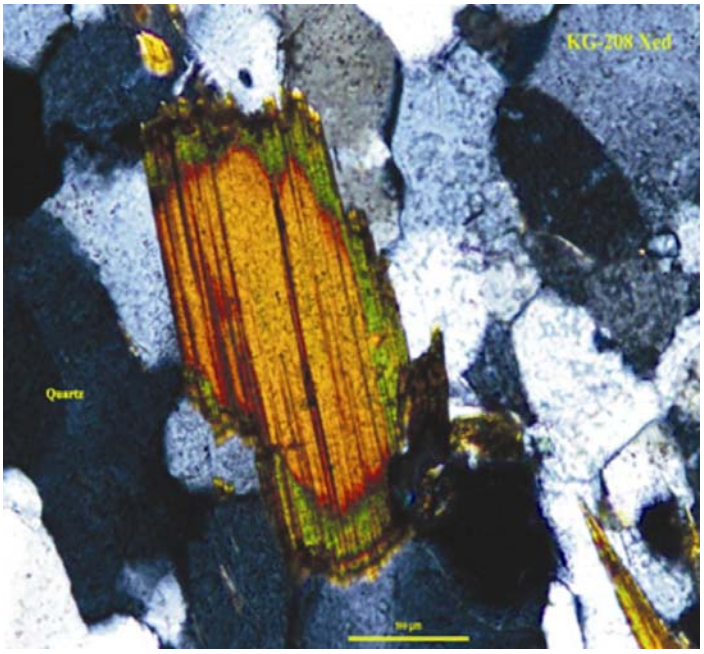

Figure 3. Astrophyllite exhibiting zoning under crossed nicols.

pegmatites, as in Kola, former USSR[12]. Near-identical kuplestkite is reported from Laven Island, Norway, and also from Kangerdlugssuaq Fjord, Greenland. Astrophyllite occurring in the form of golden-yellow plates and fibrous masses associated with pectolite, sphene and natrolite is noticed in the nepheline syenites of Hibina-Toundra Province, Kola Peninsula, Russia[13]. The controls of high field strength elements in the magma, and subsequently into the alkali titano-, zircono and niobosilicates such as the astrophyllite group, may contribute to an understanding of the paragenesis of these minerals[11].

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