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Research Article

Groundwater Flow Mechanism at a Proposed Mining Site in Southwestern Sierra Leone

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Abstract

Dry mining of titanium group minerals have been introduced in Sierra Leone aimed at replacing dredging, which has been characterized by serious environmental challenges. Considering the importance of keeping the ore dry during the mining process, a baseline study was commissioned in and around the proposed mining site to assess the hydrogeological characteristics of the area. This paper presents the findings of a baseline hydrogeological assessment of the mining site and its immediate environs.

Static water levels were measured in boreholes drilled during the mineral exploration phase, which are used in this study to develop a groundwater flow mechanism of the area. Depth to the water table ranges from 1.3m below ground level (bgl) to 11.5m (bgl). A groundwater contour map was developed from the computer code: Surfer8, which is interpreted to show that although flow within the Aquifer is fissure-controlled, lateral flow seems to be rather sluggish compared to the well-established vertical gradients. Lateral flow within the shallow aquifer is from east to west with three zones identified to be possible recharge areas.

Knowledge of the flow mechanism will enable us to understand the degree to which seasonal variation of the water table will compromise open cast dry mining unless a dewatering protocol is adopted that would ensure the dryness of the ore prior to and during excavation. Monitoring boreholes should be drilled at carefully selected locations to capture time series data that will be used in making informed decisions on the correct timing as well as the most appropriate method of ore excavation.

Keywords: Static Water Level; Shallow Aquifer; Flow Mechanism; Groundwater Contour Map; Dry Mining

Introduction

Until recently, dredging has been the exclusive method of heavy mineral sand extraction at a rutile mines in the southern region of Sierra Leone. The operating company has introduced dry mining with a view to reducing production costs in addition to addressing the environmental impacts that have characterized the dredging operation. To ensure a successful and sustainable mining operation a more nuanced approach is desirable which would include among others ascertaining the effect of groundwater movement on ore extraction. This study was commissioned to assess baseline hydrogeological characteristics of the area.

In assessing baseline hydrogeological conditions within the proposed mining site and its immediate environs, it is important to understand aspects of the flow mechanism which is also relevant in characterizing the aquifer system as well as developing a conceptual groundwater model of the area. In this study static water levels measured in boreholes drilled through the crystalline basement are used to develop a water table contour map of the proposed mining site. The water table map shows the spatial distribution of hydraulic head or the elevation of the water table. When used in conjunction with other data the contour map has helped us better understand the groundwater flow mechanism which also includes ascertaining flow directions which, the result strongly suggests, is consistent with the regional groundwater flow direction.

The result of the study could have implications for the type of mining operations envisaged in the area. The anticipated challenges that characterize open cast (dry) mining is put into context in this paper, which includes, but not limited to, large seasonal fluctuations in the groundwater table. The study has demonstrated that lateral groundwater flow is from east to west consistent with the general flow direction of the major rivers. While lateral groundwater flow is seemingly sluggish, there are substantial and well established vertical gradients. For this reason, open cast (dry) mining will be compromised, especially in the late rainy season unless measures are instituted to suppress rising groundwater levels.

The study area

The study area is the proposed Sembehun mine development site located near the village of Kamatipa, on the Bagru Creek, Moyamba District, in southern Sierra Leone (Figure 1). The area is relatively flat with surface elevation ranging from 20.9m to 36.4m above sea level. The soil may be described as gravelly feralitic reflecting the influence of tropical weathering on the formation of regolith and soil (Odell et al., 1974). Farm bush appears to be the dominant vegetation type which is gradually replacing the dense tropical forest that is so characteristic of the region. Land use practices that utilize water include crop farming and animal husbandry. Swamp and upland rice, cassava, millet, groundnut, sweet potato, maize, vegetables, oil palm, bananas, and citrus fruits are some of the subsistence crops cultivated by the community.

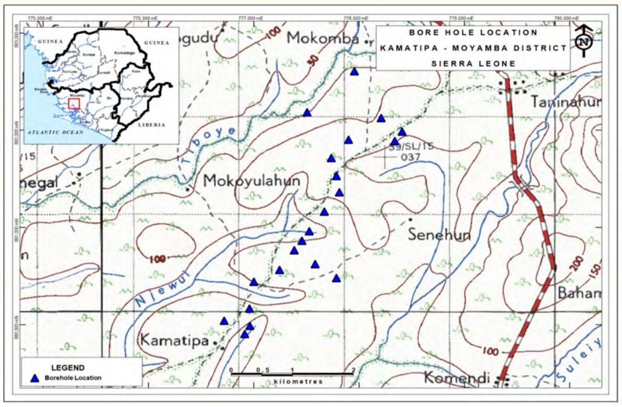

Figure 1: Map of proposed mining site within the study area showing borehole locations.

Hydrometeorology

The climate in the area reflects to a considerable degree the general climatic situation in the country with two clearly defined seasons: The rainy season commences in May and ends in November, whilst dry conditions are experienced between December and April. Between late December and early February, dry, north easterly winds from the Sahara Desert, locally referred to as Harmattan, causes a sudden drop in relative humidity. Moyamba District has no hydrometeorological station and the nearest station to the study area is located some 50km away in Bonthe District to the west, where daily readings were recorded.

Table 1 and Figure 2 show mean monthly temperature (1999-2005) for the region (Statistics Sierra Leone, 2008). The figures indicate that the mean annual temperature for the period was 27.0°C. The lowest temperature was recorded in July (25.8°C) whilst March appears to be the warmest with a temperature of 28.2°C. Relative Humidity is fairly high particularly in the months of June, July, August, and September (Table 1 and Figure 2). The highest value (89%) was measured in July and the lowest, 71%, was recorded in March [1].

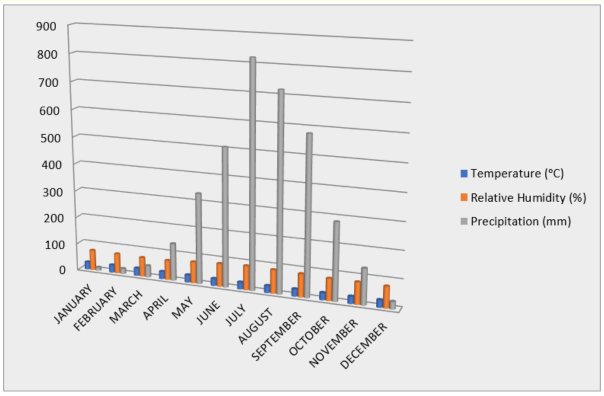

Figure 2: Relationship between mean monthly temperature, relative humidity, and precipitation for the study area.

Month	Temperature (°C)	Relative Humidity (%)	Precipitation (mm)
January	27	75	11.9
February	27.7	73	19.2
March	28.2	71	42.6
April	27.8	72	137.7
May	27.2	79	333.1
June	26.5	85	508.4
July	25.8	89	822.2
August	25.9	87	720.3
September	26.9	85	579.9
October	26.5	81	285
November	26.8	81	132.7
December	27.5	79	27.2
Total			**3620.2**

Table 1: Mean monthly temperature, relative humidity, and precipitation for the study area [1].

The principal means of groundwater recharge is infiltration of available precipitation on the aquifer. Sierra Leone lies along the humid tropics where the form of precipitation is invariably rainfall. Table 1 reveals that during the period 1991-2010 the area receives a mean annual total precipitation of 3620.2mm. Figure 2 shows that rainfall has a unimodal distribution, with the peak occurring in July. The highest rainfall measured 822.2 mm and was recorded in July, while the lowest value (11.9 mm) was recorded in January. The data also points to the fact that 93% of this rainfall occurred between the months of May and November. Evapotranspiration limits to a considerable degree the amount of precipitation available for infiltration and for supplementing groundwater storage. There is no available data on evapotranspiration for the study area.

The area is drained by the Bagru Creek (Figure 1), one of several creeks found along the coastal plain of Sierra Leone. The Bagru Creek has a total length of 89 km and a drainage area of 78 km^2 (Statistics Sierra Leone, 2008). The lower reaches of the river is influenced by tidal conditions from the Atlantic Ocean. There are smaller permanent streams draining the area which form a dense network flowing in a generally southwest direction.

Geology

The area is underlain by the Kasila Group, a linear belt dominated by high-grade metamorphic rocks of Archaean age [2]. Generally, outcrops in this terrain are poorly exposed. However, lithological boundaries have been drawn between major rock types such as metasedimentary and basic granulite. Some of the individual lithologies such as leucogabbro and banded iron formation assume a lensoid form rather than continuous layers elongate along the NW-SE foliation trend.

Keyser and Mansaray (2004) have shown that the western part of the Group which falls within the study area is composed of gneisses, migmatites, and granulites of quartzo-feldspathic composition. These are interbanded with calc-silicates, banded iron formation and quartzitic materials. The quartzo-feldspathic and quartzose rocks have been interpreted [3,4] on the basis of their composition and association as being dominantly of sedimentary origin.

However, Williams [5], from field evidence, suggest an igneous origin for some of the thinner, discordant units of quartzo-feldspathic composition. Hurley., *et al*. [6], from potassium-argon age determinations give an age of 550 Ma For the Kasila Group, which, according to Williams and Culver [7] reflects Pan-African (Rokellide) reworking that reactivated the shear zones on the eastern margin and produced local low-angle thrusts in Liberia.

Mineral sands are found in considerable amounts overlying bedrock, below a relatively thin layer of soil. These sands are the source of titanium minerals mined in the area. Rutile and ilmenite are the principal titanium minerals occurring in the area, while zircon and monazite are found in smaller quantities. The mineral sands in the study area have been characterised as the Sembehun Deposits to reflect the principal town in which they occur.

Hydrogeology

The Aquifer may be defined as crystalline basement comprising fractured bedrock and the overlying weathered layer (regolith) which in the study area comprises a relatively thick layer of poorly consolidated sand. The mineral-rich sands are fine to medium grained and are found to occur below a relatively thin layer of soil. Data on the porosity and permeability of the sands are unavailable. However, the occurrence of groundwater at shallow depths is suggestive of high infiltration rates occasioned by the relatively high permeability of the sands. The fresh bedrock found at greater depths has a high permeability underpinned by deep seated fractures. The crystalline bedrock has become a sustainable source of groundwater in other areas within the same geological formation which is harnessed by drilling boreholes that intercept deep-seated fractures [8].

Groundwater manifestations can be seen naturally as springs and seeps. Some of the permanent streams originate as springs. Precipitation appears to be the principal factor controlling recharge into the aquifer. Aquifer recharge takes place annually by normal infiltration processes after soil moisture deficit has been satisfied [9], during, and shortly after the period of heavy rains (May to October). Recharge from precipitation is augmented by surface water from the network of streams in the area. There is no historical data on the amount of water entering the aquifer annually.

Many of the spring sources emerge only in the rainy season when the shallow water table rises above the ground surface. To a considerable extent the aquifer is unconfined and the water table appears to follow in a subdued form, the surface topography. This observation is corroborated by field measurements of static water level, which indicate that depth to water is greater in the interfluves than in the valleys. Static water levels measured in wells in the area (Table 3) varies from 3.0 (mbgl) at a valley location to 14.6 (mbgl) at an interfluvial location.

There are no time series data for groundwater levels in the study area, attributable to a dearth of monitoring stations. However, from data obtained from other parts of the region, groundwater levels start to rise in May when the rains commence up until end of September when the aquifer is fully recharged. Evidence from other areas indicates large seasonal fluctuation [8,10]. Groundwater flow rates in Sierra Leonean Aquifers have not yet been documented. However, fissure flow appears to be widespread in fractured bedrock, where groundwater residence time is shorter, whilst in the weathered mantle, diffused flow necessitates a longer residence time. The response of the water table to changes in storage suggests that flow within the aquifer is dominantly vertical.

Methodology

Static water levels (SWL) were measured in boreholes (Table 2) drilled through crystalline bedrock as part of the mineral exploration programme. It was ensured that the water columns in these boreholes remain undisturbed prior to measurements of SWL. The borehole data is integrated with map evidence of surface water resources to develop a groundwater flow mechanism of the area. Each data point is uniquely marked using a Garmin Global Positioning System (Table 2).

No.	Borehole ID	Coordinates		Surface Elevation (m)	Depth of borehole (m b.g.l.)	Static Water Level (m b.g.l.)	Water level elevation (m a.s.l.)
		Eastings	Northings				
1	KB-001	778337.8	881896.7	33.6	9.5	7.5	26.1
2	KB-002	777955	882616.9	20.9	4.5	1.3	19.6
3	KB-003	777897.7	881910.5	36.0	15.0	11.0	25.0
4	KB-004	777503.2	882192.7	17.0	6.0	2.0	15.0
5	KB-005	777734.9	881724.3	36.4	12.0	10.4	26.0
6	KB-006	777810.5	881369.3	31.9	12.0	11.0	20.9
7	KB-007	777381.6	880775.6	24.6	10.5	9.1	15.5
8	KB-008	777454.8	880872.5	21.2	4.5	2.0	19.2
9	KB-009	777526.6	880971.3	21.1	4.5	0.9	20.2
10	KB-010	777670	881172.1	31.0	13.5	8.35	22.7
11	KB-011	777782.6	880490.2	31.0	10.5	10.1	20.8
12	KB-012	777581.9	880632.6	33.0	12.0	10.5	22.5
13	KB-013	777243	880573.5	30.0	15.0	11.5	18.4
14	KB-014	776998	880448.6	22.4	10.5	9.0	13.4
15	KB-015	776957.5	880176.1	27.2	16.5	10.1	17.1
16	KB-016	776716	880049.7	28.0	16.5	11.0	17.0
17	KB-017	776962.2	879995.6	26.1	13.5	9.5	17.0
18	KB-018	776911.4	879913.9	24.0	10.5	6.2	18.0
19	KB-019	777782.7	881539.5	36.3	16.5	11.5	25.0
20	KB-020	778408.2	881993.2	36.0	10.5	8.0	28.0
21	KB-021	778208	882135.8	29.4	7.5	5.5	24.0

Table 2: Borehole drilling record.

Groundwater level elevation (hydraulic head) values were determined from static water level measurements. The head relationship (see Figure 3) is given as:

$h = \psi + z$

Where

h = Hydraulic head (m)

ψ = Pressure head (m)

z = Elevation head (m)

Surface elevation values were measured to within +/- 3m using the Global Positioning System. The X-Y coordinates and surface and groundwater level elevation values were fed into the computer program, Surfer, version 8 [11].

Both surface water and groundwater sources were sampled on site and measurements made soon afterwards to determine a set of physical parameters, including: Temperature, Total Dissolved Solids, Electrical Conductivity, and pH. These parameters are used as an indication of salinity, symptomatic of the amount of dissolved solids present in the water. Although this was not a key objective, the determination of these physical parameters provides a rough assessment of the suitability of the water for drinking and other domestic use. The concentration of each parameter in the groundwater is compared with the World Health Organisation's Guidelines for Drinking Water Quality [12].

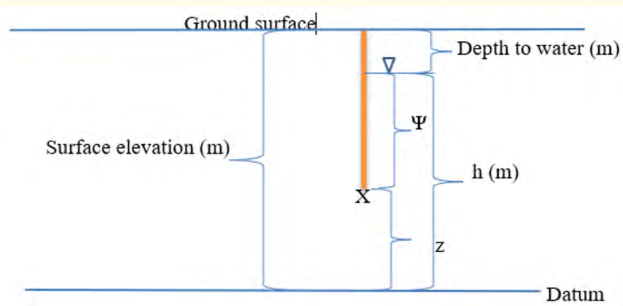

Figure 3: Schematic showing fundamental head relationships.

X = point of measurement

h = Hydraulic head (m)

ψ = Pressure head (m)

z = Elevation head (m)

Result

Data obtained from boreholes were augmented by existing hydrogeological data which indicate that groundwater occurs at relatively shallow depths within the Crystalline Basement. Static water levels range from 1.3m below ground level (bgl) in borehole KB-002 to 11.5m (bgl), measured in boreholes KB-013 and KB-019 (Table 2). It is observed also, that the deeper water tables are found at higher surface elevations (interfluves), whilst shallow water tables are intercepted in boreholes drilled in valley locations. This strongly suggests that the water table follows closely the surface topography, but in a subdued form. The relatively small differences in the water level elevation values (Figure 4) is indicative of smaller hydraulic gradients, suggesting that horizontal flow is rather sluggish compared to the relatively large vertical gradients reminiscent of recharge into and discharge from the aquifer.

A groundwater contour map was produced as output from computer modeling (Figure 5) with the contours showing lines connecting points of equal water level elevation (hydraulic head). Changes in the spacing of equipotential lines represent a change in the hydraulic gradient. The steeper the hydraulic gradient, the greater the flow whilst milder gradients suggest sluggish flow. Groundwater flow is in the direction of a decrease in hydraulic head, and is known to be perpendicular to the equipotential lines. The contour map clearly demonstrates that groundwater flows from east to west. That is, from the most elevated zones, to, and diverges from recharge areas, and converge as they approach an area of concentrated discharge (Figure 5).

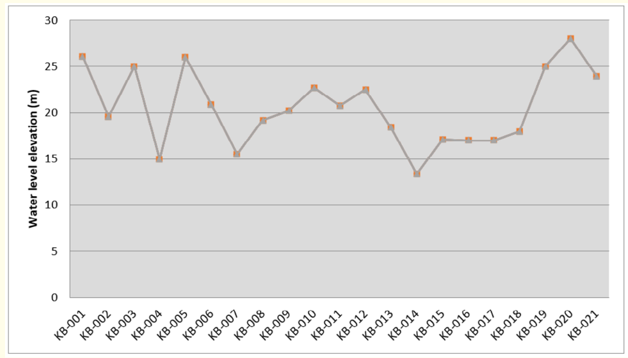

Figure 4: Water level elevation (masl) in boreholes at the proposed mining site.

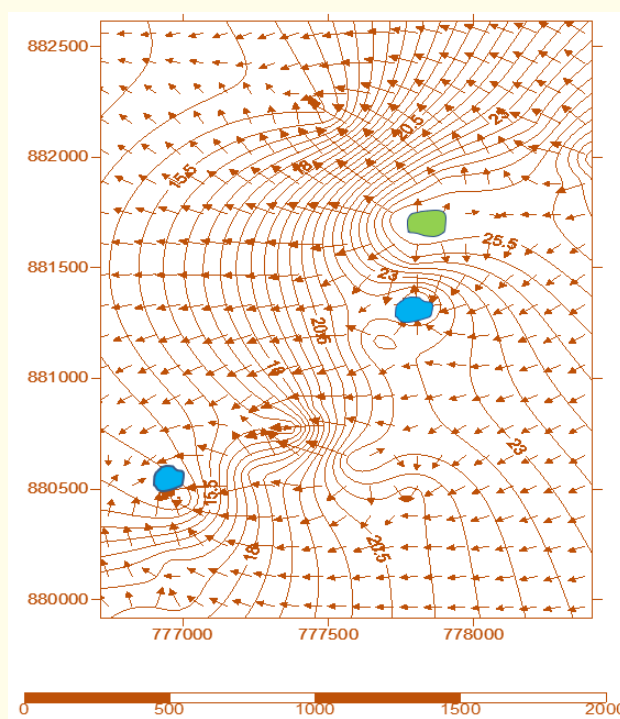

Figure 5: A vector map superimposed on a water table contoured map of the study area. The figures represent hydraulic head values measured in metres. The arrows indicate flow directions. The blue patches depict groundwater discharge zones, while the green patch represents a zone of groundwater recharge.

In Sembehun Town, three shallow dug wells with an average depth of 13m (bgl) were found to be dry. These wells are located in a topographically high (recharge) area where the component of flow is downward. On the other side of town the water table was found at a shallow depth of 3m (bgl), in a well dug in a topographically low (discharge) area. The flow path was also monitored using hydrochemical trends, and although the data are few, it appears that salinity increases along the flow path, with water from recharge areas being relatively fresh while that from discharge areas has a higher solute content.

The result of on-site analysis of water samples indicates that all but one of the water sources has pH in the range normally expected for drinking water (Table 3). pH ranges from 6.6 measured at Nancy Tucker to 4.5 at a valley location. Electrical Conductivity ranges from 17.4μScm^{-1} to 102.8μScm^{-1} while Total Dissolved Solids (TDS) ranges from 11.6mgl^{-1} to 68.5mgl^{-1}. The classification system devised by Todd [13] is applied in this study to determine the salinity of the groundwaters, and based on the values for Total Dissolved Solids (TDS), the water sources are deemed to be invariably fresh [14].

Location	GPS Coordinates	Surface Elevation (masl)	Water Source	Depth to water (m)	Sample ID	Date	Temp C	pH	EC μS/cm	TDS mgl^{-1}
Mokamatipa	0776804 0879744	38	Dug well	6..5	KG1	25/07/15	29.8	5.6	24.8	16.5
Moyaebay		24	Stream		KS1	25/07/15	27.2	6.5	17.4	11.6
Sembehun (Nancy Tucker)	0771518 0878446	26	Dug well	10.2	SG1	26/07/15	26.1	6.6	61.4	40.9
Sembehun (Chief's Compound)	0771172 0877090	32	Dug well (Faulty Pump)	14.6	N/D	N/D	N/D	N/D	N/D	N/D
Sembehun (By Section Chiefs House)	0771499 0878186	19	Dug well	Not determined (Sealed)	SG2	26/07/15	26.7	5.4	31.0	20.7
Sembehun Health Centre	0771472 0878369	22	Dug well	10.0	SG3	26/07/15	26.8	5.6	32.6	21.7
Sembehun (Near Swamp)	0771773 0878261	21	Dug well	3.0	SG4	26/07/15	27.5	4.5	102.8	68.5

Table 3: Result of Water quality tests in dug wells in the study area.
N/D = Not determined

Discussion and Conclusions

Water level elevation (hydraulic head) values determined from static water levels in boreholes are used in conjunction with other data to determine the groundwater flow mechanism in the area. The water table contour map generated from the computer program Surfer, version 8, suggests lateral flow consistent with the regional flow direction of the major rivers, i.e. from east to west. In the study area, like other parts of the country with similar climatic regime the Crystalline Basement Aquifer is characterised by large vertical gradients especially in the rainy season, which could have implications for the anticipated dry open cast mining programme in the area.

The spacing of the contours on the water table map provides a clear indication of the hydraulic gradient. Three zones are recognized that are characteristic of steep hydraulic gradients, and where flow seems to be appreciable (Figure 6). Where the hydraulic gradients are milder flow is expected to be rather sluggish. Three zones were identified within the area (Figure 6) where flow seems to be diverging and these are interpreted as possible recharge areas, and where the component of flow is downward.

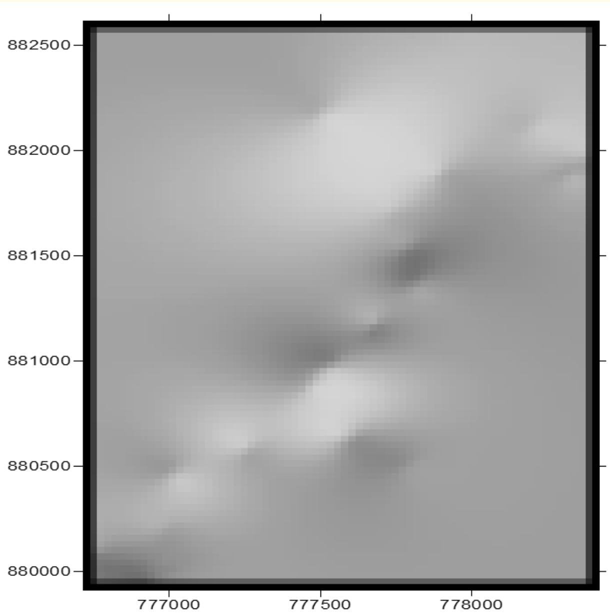

Figure 6: Image map showing high points (recharge areas) and depressions (discharge areas).

The study has underscored the need for a national groundwater monitoring system which will, among other things, assist in characterizing the flow mechanism derived from an analysis of the water table contour map. To thwart the threat of rising groundwater levels occasioned by large vertical gradients, a dewatering programme is recommended during the months (July to September) of very heavy rains which are so characteristic of the region. This will ensure that the ore is kept dry prior to and during excavation.

The mapping tool employed in this study has enabled us to better understand the spatial relationships between groundwater recharge and discharge in the study area, including also, flow directions, future pumping regimes, and the anticipated impacts of dry mining and other land use practices on both the quantity and quality of groundwater. Water level contoured maps can expose changes in groundwater flow regimes occasioned by natural or anthropogenic influences The methodology is relatively simple to use and could be replicated in other areas with similar hydrogeological characteristics.

Acknowledgement

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