

NIGERIA MARITIME UNIVERSITY

Okerenkoko, Warri South-West, Delta State

Department of Marine Geology

MGY 103

Introduction to Marine Geochemistry

Applications of Geochemistry: Lecture Note

Environmental and Groundwater Studies · Mineral Exploration
Engineering Geology · Petroleum Exploration

Dr. AMIWERO Daniel Tuoyo

Lecturer, Department of Marine Geology

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Course information

This note covers the applied part of MGY 103. It shows how the chemistry of rocks, soils, sediments, water and fluids is used to solve practical problems in the environment, mineral exploration, engineering works and petroleum exploration.

Item	Detail
Course	MGY 103: Introduction to Marine Geochemistry
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Department	Marine Geology
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Learning outcomes

At the end of this part of the course, you should be able to:

1. Explain the geochemical cycle and the difference between the primary and secondary geochemical environments.
2. Describe how Eh, pH, adsorption and complexing control the mobility of elements at the Earth's surface.
3. Choose a suitable sampling medium and analytical method for a given geochemical problem, and describe basic quality control.
4. Classify groundwater using major-ion chemistry and recognise signs of saltwater intrusion and pollution.
5. Explain how geochemical dispersion halos and pathfinder elements lead explorers to ore deposits.
6. Identify geochemical hazards to engineering structures, including sulphate attack, chloride corrosion, dispersive soils and acid sulphate soils.
7. Evaluate a petroleum source rock from TOC and Rock-Eval data, and explain how biomarkers link an oil to its source.
8. Relate each application to the Niger Delta and the wider Nigerian setting.

Why geochemistry matters to a marine geologist

The Niger Delta is one of the most chemically active settings in Nigeria. Fresh river water meets seawater, organic-rich mangrove mud stores sulphur and metals, and the sediments host one of the world's major petroleum systems. Oil production, coastal construction, dredging and rapid urban growth all change the chemistry of water and soil.

A graduate of this department will be asked practical questions. Is this borehole water safe to drink? Has seawater reached the aquifer? Will this soil attack the concrete of a jetty? Is this shale rich enough to generate oil? Each answer comes from geochemical data, read correctly.

Section 1: Foundations of applied geochemistry

Applied geochemistry uses the distribution of chemical elements and compounds in natural materials to answer practical questions. Every application in this note rests on the same few principles: elements are released from rocks, move in water and air, and are fixed again in new materials. Learn these principles first, and each application becomes a variation on one theme.

1.1 What applied geochemistry is

Geochemistry is the study of the abundance, distribution and movement of chemical elements and isotopes in the Earth. **Applied geochemistry** turns that knowledge to use. It finds ore, assesses pollution, protects structures, and locates petroleum.

Three questions run through every applied study:

1. **What is normal?** The natural concentration of an element in a given material and area is its **background**.
2. **What is unusual?** A concentration clearly above or below background is an **anomaly**.
3. **Why is it unusual?** An anomaly may come from ore, from pollution, from a change in rock type, or from an analytical error. Interpretation separates these causes.

1.2 Abundance of elements and the Goldschmidt classification

The Earth's crust is dominated by eight elements: oxygen, silicon, aluminium, iron, calcium, sodium, potassium and magnesium. Together they make up about 98% of the crust by weight. Every other element, including gold, copper, lead and lithium, is a **trace element**, usually measured in parts per million (ppm) or parts per billion (ppb).

V. M. Goldschmidt grouped elements by the phases they prefer. This grouping predicts where an element will concentrate and which elements travel together.

Group	Preferred phase	Typical elements	Practical meaning
Lithophile	Silicates and oxides	Na, K, Ca, Mg, Al, Si, Li, Rb, Ba, REE, Zr	Concentrate in granites and pegmatites; dominate rock and soil chemistry
Chalcophile	Sulphides	Cu, Pb, Zn, Ag, As, Sb, Hg, Cd, S	Form sulphide ores; released as acid drainage when sulphides oxidise
Siderophile	Metallic iron	Fe, Ni, Co, Pt, Au, Pd	Concentrated in the core and in mafic and ultramafic rocks
Atmophile	Gas phase	N, noble gases, H (as water), C (as CO_2)	Govern the atmosphere and surface gas surveys
Biophile	Living matter	C, H, O, N, P, S, I	Concentrated in organic matter, coal, petroleum and mangrove mud

The classes overlap. Iron, for example, is siderophile in the core but lithophile and chalcophile in the crust. Use the scheme as a guide to association, not a strict rule.

1.3 The geochemical cycle

The **geochemical cycle** is the path an element follows as rocks form, weather, erode, settle and are buried and melted again. It has two parts.

The **primary environment** lies below the zone of weathering. It has high temperature and pressure, little free oxygen and restricted fluid flow. Magmatic, metamorphic and hydrothermal processes act here. Ore bodies form mainly in this environment.

The **secondary environment** is the Earth's surface. It has low temperature and pressure, free oxygen and carbon dioxide, abundant water and living organisms. Weathering, soil formation, erosion, transport and sedimentation act here. Most geochemical sampling, and all environmental and engineering work, takes place in this environment.

The key fact for applied work: minerals stable in the primary environment are often unstable at the surface. A sulphide that formed at 300 °C oxidises in contact with air and rainwater. As it breaks down, its metals are released and spread into soil, water and plants. That spread is what explorers detect and what environmental scientists measure.

1.4 Geochemical dispersion

Dispersion is the process that moves elements away from their source. **Primary dispersion** happens as the rock or ore forms, when hydrothermal fluids carry elements into the wall rock. **Secondary dispersion** happens at the surface through weathering and transport.

Secondary dispersion follows three main routes:

- **Mechanical dispersion:** grains are moved as solids by gravity, running water, wind or ice. Resistant minerals such as gold, cassiterite, zircon and ilmenite travel this way.
- **Hydromorphic dispersion:** elements are dissolved and carried in water, then fixed elsewhere by precipitation or adsorption.
- **Biogenic dispersion:** plants take up elements through their roots and return them to the soil surface in leaf litter.

The patterns that dispersion leaves are called **halos** when they surround a source and **trains** when they stretch downslope or downstream. Section 3 uses these patterns to find ore.

1.5 What controls element mobility at the surface

Mobility is the ease with which an element moves in the secondary environment. It depends on the element and on the conditions around it. Five controls matter most.

pH (acidity). pH measures hydrogen-ion activity. Most metals (Cu, Zn, Pb, Cd, Ni) are more soluble in acid water and precipitate as the water becomes alkaline. A few elements behave the opposite way: molybdenum, arsenic, selenium, vanadium and uranium form anions and are more mobile in alkaline water.

$$\mathrm{pH} = -\log_{10} a_{\mathrm{H^+}}$$

Here $a_{\mathrm{H^+}}$ is the activity of the hydrogen ion. In dilute water it is close to the molar concentration, so water with 10^{-7} mol/L of H^+ has a pH of 7.

Eh (redox potential). Eh measures how oxidising or reducing an environment is, in volts or millivolts. Oxidising conditions occur where water meets air. Reducing conditions occur in waterlogged mud rich in organic matter, such as mangrove swamps. Iron and manganese are mobile under reducing conditions as Fe^{2+} and Mn^{2+}, then precipitate as oxides when they meet oxygen. Uranium behaves in reverse: soluble when oxidised as U^{6+}, fixed when reduced to U^{4+}.

Adsorption. Clays, iron and manganese oxides and organic matter carry charged surfaces that hold dissolved ions. Iron and manganese oxides are especially strong scavengers of metals. A soil rich in iron oxide can trap copper, zinc and arsenic close to their source.

Complexing. Some ions join with chloride, sulphate, carbonate or organic acids to form complexes. Complexes keep metals in solution where they would otherwise precipitate. Chloride complexing in seawater and brines helps carry metals such as lead, zinc and gold.

Biological activity. Bacteria drive many redox reactions. Sulphate-reducing bacteria in marine mud convert sulphate to sulphide, which then traps metals as iron, copper and zinc sulphides. This is why estuarine muds act as long-term stores of metals.

1.6 Relative mobility of common elements

The table summarises mobility under typical surface conditions. Learn the pattern, not every entry: alkalis and alkaline earths move easily, iron and aluminium stay, and many metals depend on Eh and pH.

Relative mobility	Oxidising, acid (pH < 4)	Oxidising, neutral to alkaline	Reducing
Very high	Cl, I, Br, S, B	Cl, I, Br, S, B, Mo, V, U, Se	Cl, I, Br
High	Mo, V, U, Se, Re, Zn, Cu, Co, Ni, Hg, Ag, Au	Ca, Na, Mg, F, Sr, Ra, Zn	Ca, Na, Mg, Sr, Ra
Moderate	Ca, Na, Mg, Sr, Ra, Cd	Cu, Co, Ni, Hg, Ag, Au, As, Cd	Fe, Mn
Low	K, Rb, Ba, Si, Ge, Pb	K, Rb, Ba, Si, Ge, Pb, Fe, Mn	K, Rb, Ba, Si, Ge
Very low	Fe, Al, Ti, Zr, Th, Sn, Cr, REE	Al, Ti, Zr, Th, Sn, Cr, REE	Al, Ti, Zr, Th, Sn, Cr, REE; and S, Cu, Zn, Pb, Mo, U fixed as sulphides

Adapted from the classic scheme of Andrews-Jones (1968), as reproduced in Rose, Hawkes and Webb (1979).

1.7 Eh–pH diagrams

An **Eh–pH diagram** (also called a Pourbaix diagram) shows which form of an element is stable at each combination of Eh and pH. Lines on the diagram mark the boundaries between dissolved species and solid minerals.

The diagram for iron is the most useful for a marine geologist. In summary:

- **Oxidising, neutral to alkaline water** (most river and seawater): iron is fixed as solid ferric oxide or hydroxide (haematite, goethite, ferrihydrite). This gives soils and laterites their red-brown colour.
- **Reducing, neutral water** (swamp groundwater): iron dissolves as Fe^{2+}. Borehole water from such aquifers looks clear when pumped, then turns orange as it meets air and $Fe(OH)_3$ precipitates. This is a common complaint in Niger Delta boreholes.
- **Reducing water with sulphide present** (mangrove mud): iron is fixed as pyrite (FeS_2) or iron monosulphide, which gives the mud its black colour.
- **Very acid water** (pH below about 3): iron stays in solution even under oxidising conditions, as in acid mine drainage.

The natural range of Eh and pH at the Earth's surface is limited by the stability of water. Most natural waters fall between pH 4 and 9.

1.8 Sampling media

The **sampling medium** is the material you collect. Choose it to suit the problem, the climate and the terrain.

Medium	Best used for	Notes for the Niger Delta setting
Rock	Primary halos, source rocks, baseline lithochemistry	Rare at surface in the delta; obtained from cores and cuttings
Residual soil	Locating buried ore close to source	Common in the basement areas of the north and west; deep laterite needs careful choice of horizon
Stream sediment	Regional reconnaissance of whole catchments	Fine fraction (minus 80 mesh, below 180 µm) captures adsorbed metals
Heavy mineral concentrate	Gold, tin, tantalum and other resistant minerals	Panned from stream gravels
Surface water and groundwater	Water quality, pollution, saltwater intrusion, hydromorphic exploration	Filter and acidify samples for metals; measure pH, Eh, EC and temperature in the field
Marine and estuarine sediment	Pollution history, metal sinks, seabed mineral exploration	Collected with grabs and corers; layering records past input
Vegetation	Biogeochemical exploration and plant uptake of pollutants	Same species and same plant part must be sampled throughout
Soil gas and headspace gas	Petroleum seepage, radon, buried sulphides	Light hydrocarbons, CO_2, Hg vapour

1.9 Analytical methods

The method you choose decides which elements you can measure and how low you can go. The table lists the methods you will meet most often.

Method	What it measures	Typical detection level	Common use
Atomic absorption spectrometry (AAS)	One element at a time in solution	ppm to ppb	Metals in water, soil digests

Method	What it measures	Typical detection level	Common use
Inductively coupled plasma optical emission spectrometry (ICP-OES)	About 30 elements at once in solution	ppm to tens of ppb	Multi-element surveys, major and minor elements
Inductively coupled plasma mass spectrometry (ICP-MS)	About 60 elements, plus isotopes	ppb to ppt	Trace metals, REE, pathfinders, isotope ratios
X-ray fluorescence (XRF), laboratory and portable	Major and many trace elements in solids	Tens of ppm (portable is higher)	Rock and soil chemistry; rapid field screening
Ion chromatography	Anions: Cl^-, SO_4^{2-}, NO_3^-, F^-	Sub-ppm	Water chemistry
Titration and field kits	Alkalinity (HCO_3^-), hardness	ppm	Water chemistry in the field
Gas chromatography (GC, GC–MS)	Hydrocarbons, biomarkers, organic pollutants	ppb and lower	Petroleum geochemistry, oil-spill fingerprinting
Rock-Eval pyrolysis and TOC analyser	Organic carbon content and maturity	0.01 wt% TOC	Source rock evaluation
X-ray diffraction (XRD)	Mineral identity	About 1 to 5% of a mineral	Clay mineralogy for engineering work

Remember that a total analysis and a partial extraction give different numbers. A strong acid digest that dissolves silicates reports the total metal. A weak extraction reports only the loosely held fraction, which is often the part most useful for exploration and for judging what plants and animals can take up.

1.10 Quality assurance and quality control

A geochemical number is only as good as the care behind it. **Quality assurance (QA)** is the plan for getting reliable results. **Quality control (QC)** is the set of checks that prove the plan worked.

Every batch of samples sent to a laboratory should include:

- **Field duplicates:** a second sample from the same site, to measure sampling variation.
- **Certified reference materials (standards):** samples of known composition, to check accuracy.
- **Blanks:** material with no analyte, to detect contamination in sampling or in the laboratory.
- **Laboratory replicates:** the same pulp analysed twice, to measure analytical precision.

Insert QC samples blind, so the laboratory cannot tell them apart from the rest. A common rule is one QC sample in every 20.

Accuracy is how close a result is to the true value. **Precision** is how close repeated results are to each other. A method can be precise but inaccurate, which is why both standards and duplicates are needed.

1.11 Treating geochemical data

Geochemical data are rarely normally distributed. Most trace-element data are positively skewed, with many low values and a few high ones. They are often closer to a **lognormal** distribution, so logarithms of the values are used in statistics.

The simplest way to separate background from anomaly is the **threshold**: the upper limit of normal background variation. A classic working definition is the mean plus two standard deviations, calculated on the log-transformed data.

$$T = \bar{x} + 2s$$

Here T is the threshold, $\bar{x}$ is the mean and s is the standard deviation. Values above T are treated as possibly anomalous. About 2.5% of a normal population lies above this line by chance alone, so anomalies must still be checked against geology.

Worked example. Thirty stream sediments from a basement catchment give $\log_{10}$ Cu values with a mean of 1.30 and a standard deviation of 0.15.

$$T_{\log} = 1.30 + 2(0.15) = 1.60$$

$$T = 10^{1.60} \approx 40 \text{ ppm Cu} \qquad \text{background mean} = 10^{1.30} \approx 20 \text{ ppm Cu}$$

A sample reporting 95 ppm Cu is well above threshold and deserves follow-up.

Modern practice adds robust and graphical methods: cumulative probability plots, box plots, and the median plus a multiple of the median absolute deviation. These handle skewed data and outliers better than the mean. Multi-element methods such as principal component analysis group elements that rise and fall together, which helps tell an ore signature from a rock-type change.

1.12 Key points of Section 1

- Background is normal; an anomaly is a departure from it that needs explaining.
- Ore forms mainly in the primary environment; sampling happens mainly in the secondary environment.
- pH, Eh, adsorption, complexing and bacteria decide which elements move and which stay.
- Choose the sampling medium, the analytical method and the QC plan before you go to the field.

Section 2: Geochemistry in environmental and groundwater studies

Geochemistry tells us where water came from, what it has passed through, and whether it is safe to use. In the Niger Delta, where most households drink borehole water and oil operations sit beside farms and creeks, these questions are part of daily life. This section covers groundwater chemistry, water-quality assessment, saltwater intrusion, contamination of soils and sediments, and the geochemical study of oil pollution.

2.1 Why water chemistry changes

Rainwater is almost pure, slightly acidic because it dissolves carbon dioxide. As it soaks into the ground it reacts with soil and rock. It dissolves carbonates, weathers feldspars and micas, exchanges ions with clays, and picks up salts. The longer it stays underground and the more reactive the rock, the more dissolved solids it carries.

Four natural processes dominate:

1. **Mineral dissolution and weathering.** Calcite dissolves to give Ca^{2+} and HCO_3^-. Feldspar weathers to clay and releases Na^+, K^+, Ca^{2+} and silica.
2. **Ion exchange.** Clays swap the cations they hold for those in the water. When seawater invades a fresh aquifer, clays take up Na^+ and release Ca^{2+}. When fresh water flushes a once-saline aquifer, the reverse happens.
3. **Redox reactions.** As oxygen is used up by organic matter, the water becomes reducing in a fixed order: oxygen, then nitrate, then manganese and iron oxides, then sulphate, then methane forms.
4. **Evaporation and mixing.** Evaporation concentrates salts. Mixing with seawater or with polluted water changes the whole chemical signature.

2.2 Parameters measured in a water study

Group	Parameters	Why they matter
Field parameters	Temperature, pH, Eh or dissolved oxygen, electrical conductivity (EC), turbidity	Change quickly after sampling; must be measured on site
Major cations	Ca^{2+}, Mg^{2+}, Na^+, K^+	Define water type and hardness
Major anions	HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-	Define water type; Cl^- and NO_3^- flag seawater and pollution
Bulk properties	Total dissolved solids (TDS), total hardness, alkalinity	Overall quality and taste
Trace and toxic elements	Fe, Mn, Pb, Cd, Cr, As, Hg, Ni, Zn, Cu	Health limits and aesthetic problems
Nutrients	NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}	Sewage, fertiliser and waste-dump pollution
Organic pollutants	Total petroleum hydrocarbons (TPH), BTEX, PAHs	Oil spills, refinery and artisanal refining waste

Group	Parameters	Why they matter
Microbiology	Total and faecal coliforms	Sewage contamination from nearby pit latrines

A quick estimate links EC and TDS. For most fresh waters:

$$\text{TDS (mg/L)} \approx k \times \text{EC } (\mu\text{S/cm}), \qquad k = 0.55 \text{ to } 0.75$$

Use the factor for screening only, never in place of measured TDS.

2.3 Units and the ion balance check

Laboratories report ions in milligrams per litre (mg/L). To compare ions with different charges, convert to milliequivalents per litre (meq/L):

$$\text{meq/L} = \frac{\text{mg/L} \times \text{ionic charge}}{\text{atomic or formula weight}}$$

For example, for 40 mg/L of calcium (charge 2, atomic weight 40.08):

$$\text{Ca}^{2+} = \frac{40 \times 2}{40.08} = 2.0 \text{ meq/L}$$

Water is electrically neutral, so total cations should equal total anions in meq/L. The **charge balance error (CBE)** checks the quality of an analysis:

$$\text{CBE (\%)} = \frac{\sum\text{cations} - \sum\text{anions}}{\sum\text{cations} + \sum\text{anions}} \times 100$$

An error within ±5% is normally accepted. A larger error means an ion was missed, measured wrongly, or recorded in the wrong unit. Check the analysis before you interpret it.

2.4 Classifying water: hydrochemical facies

A **hydrochemical facies** is a water type named by its dominant cation and anion, such as Ca–HCO_3 or Na–Cl. Facies reveal the history of the water.

Facies	Usual meaning
Ca–HCO_3 or Ca–Mg–HCO_3	Young recharge water; carbonate or feldspar weathering
Na–HCO_3	Fresh water that has exchanged Ca for Na on clays; often freshening of a once-saline aquifer
Ca–Cl or Mg–Cl	Reverse ion exchange; typical of the early stage of seawater intrusion
Na–Cl	Seawater, brine, evaporation, or heavy pollution by salt or sewage
Ca–SO_4 or mixed SO_4	Gypsum dissolution, oxidation of pyrite, acid sulphate soils, or industrial waste

The **Piper trilinear diagram** is the standard way to show facies. It plots cations in one triangle, anions in another, and projects both into a central diamond. Samples of similar type plot together, and mixing between two waters plots as a straight line. The **Stiff diagram** shows each sample as a polygon whose shape fingerprints its type, which is useful on maps. The **Gibbs diagram** plots

TDS against Na/(Na + Ca) and Cl/(Cl + HCO_3) to show whether rainfall, rock weathering or evaporation controls the chemistry.

Groundwater in the Benin Formation, the main aquifer of the Niger Delta, is generally fresh with low TDS. It is often slightly acidic, commonly with a pH between about 4.5 and 6.5, because rain enters through sandy soils with little carbonate. Dissolved iron is often high. Near the coast and the creeks, Na–Cl and mixed facies appear where saline water has entered the aquifer.

2.5 Drinking-water quality

Results are judged against standards. In Nigeria the reference is the **Nigerian Standard for Drinking Water Quality (NSDWQ, NIS 554:2015)**, read alongside the World Health Organization (WHO) guidelines. The table gives selected maximum permitted levels from the NSDWQ. Always confirm values against the current edition before you use them in a report.

Parameter	NSDWQ maximum (mg/L unless stated)	Concern
pH	6.5 to 8.5 (no unit)	Acid water corrodes pipes and leaches metals
Electrical conductivity	1000 µS/cm	Salinity
Total dissolved solids	500	Taste and salinity
Total hardness (as $CaCO_3$)	150	Scaling; poor lathering
Chloride	250	Taste; seawater intrusion
Sulphate	100	Taste; laxative effect
Nitrate	50	Infant methaemoglobinaemia (“blue baby”)
Fluoride	1.5	Dental and skeletal fluorosis
Iron	0.3	Taste, orange staining
Manganese	0.2	Black staining; neurological effects at high dose
Lead	0.01	Nervous system damage, especially in children
Arsenic	0.01	Skin lesions and cancer
Cadmium	0.003	Kidney damage
Chromium	0.05	Cancer risk (as Cr^{6+})
Mercury	0.001	Nervous system and kidney damage

High iron is the most common complaint in delta boreholes. It comes from reducing groundwater dissolving iron oxide coatings on aquifer sand (Section 1.7). It is mainly an aesthetic problem. It is treated by aeration, which oxidises Fe^{2+} to insoluble $Fe(OH)_3$, followed by settling and sand filtration:

$$4\,Fe^{2+} + O_2 + 10\,H_2O \rightarrow 4\,Fe(OH)_3 + 8\,H^+$$

Water Quality Index (WQI). A WQI combines many parameters into one number for easy reporting. Each parameter is compared with its standard, weighted by its importance to health, and summed. A low WQI means good water. The index is useful for maps and for the public, but it hides which parameter is the problem, so always report the parameters too.

2.6 Saltwater intrusion

Saltwater intrusion is the movement of seawater into a fresh aquifer. It is a serious risk along the Nigerian coast, where sea level is rising, creeks carry tidal brackish water inland, and pumping lowers the water table.

Under natural conditions, light fresh water floats on denser seawater. The **Ghyben–Herzberg relation** estimates the depth of the fresh–salt interface below sea level from the height of the water table above sea level:

$$z = \frac{\rho_f}{\rho_s - \rho_f} h \approx 40\, h$$

Here z is the depth of the interface below sea level, h is the height of the water table above sea level, ρ_f is the density of fresh water (1.000 g/cm^3) and ρ_s is the density of seawater (1.025 g/cm^3). The factor 40 comes from 1.000/(1.025 − 1.000). Lowering the water table by 1 m through pumping can raise the interface by about 40 m. This is why closely spaced boreholes in coastal towns turn salty.

Seawater has a distinctive chemistry. Its main ions, in round numbers, are chloride about 19,000 mg/L, sodium about 10,500 mg/L, sulphate about 2,700 mg/L, magnesium about 1,300 mg/L, calcium about 400 mg/L and potassium about 400 mg/L. Bicarbonate is low, about 140 mg/L.

Geochemical indicators of intrusion:

- **Rising chloride and EC** over time in a monitored borehole.
- **Revelle ratio**, with all concentrations in meq/L. Values below 0.5 suggest fresh water; values between about 0.5 and 6.6 suggest slight to moderate contamination; values above 6.6 suggest strong contamination.

$$\text{Revelle ratio} = \frac{\text{Cl}^-}{\text{HCO}_3^- + \text{CO}_3^{2-}}$$

- **Na/Cl molar ratio** near 0.86, the seawater value. Fresh water from silicate weathering usually has Na/Cl above 1.
- **Ca–Cl facies** with an excess of Ca over Na, caused by reverse ion exchange at the front of an advancing salt wedge.
- **Bromide/chloride ratio** close to that of seawater, which separates seawater from salt from sewage or road salt.

Geophysics complements geochemistry here. Electrical resistivity surveys map the low-resistivity saline zone between boreholes, and geochemistry confirms its source.

2.7 Contamination of soils and sediments

Soils, river bed sediments and estuarine muds trap metals and organic pollutants. They give a longer and more stable record than water, which changes with every tide and rainfall. To judge contamination, compare the measured value with a background value. Four indices are in common use.

Contamination factor (CF). The ratio of the measured concentration to the background.

$$\mathrm{CF} = \frac{C_{\text{sample}}}{C_{\text{background}}}$$

CF below 1 means low contamination, 1 to 3 moderate, 3 to 6 considerable, and above 6 very high.

Geoaccumulation index ($\mathbf{I_{geo}}$). Proposed by Müller (1969). C_n is the measured concentration of element n and B_n is its background. The factor 1.5 allows for natural variation in background.

$$I_{\text{geo}} = \log_2\left(\frac{C_n}{1.5\,B_n}\right)$$

$\mathrm{I_{geo}}$ of 0 or less is unpolluted. Each unit above that is a further class, up to above 5, which is extremely polluted.

Enrichment factor (EF). This normalises the metal to a conservative element, usually aluminium or iron, to cancel the effect of grain size. Fine muds naturally hold more metal than sands, and EF corrects for this.

$$\mathrm{EF} = \frac{(C_{\text{metal}}/C_{\text{Al}})_{\text{sample}}}{(C_{\text{metal}}/C_{\text{Al}})_{\text{background}}}$$

EF near 1 points to a natural, crustal source. EF above about 1.5 suggests an added source, often human.

Pollution load index (PLI). The geometric mean of the CF values of n metals at a site. PLI above 1 means the site is polluted overall.

$$\mathrm{PLI} = (\mathrm{CF}_1 \times \mathrm{CF}_2 \times \cdots \times \mathrm{CF}_n)^{1/n}$$

Worked example. A mangrove mud near a jetty contains 60 mg/kg lead. The local background for lead in delta muds is taken as 20 mg/kg.

$$\mathrm{CF} = \frac{60}{20} = 3 \quad \text{(considerable contamination)}$$

$$I_{\text{geo}} = \log_2\left(\frac{60}{1.5 \times 20}\right) = \log_2 2 = 1 \quad \text{(unpolluted to moderately polluted)}$$

The two indices differ because $\mathrm{I_{geo}}$ builds in the 1.5 factor. Always state which index you used and which background.

The choice of background is the weakest link. Use local pre-industrial values from the base of a dated core where possible. Average crustal or shale values (for example, Turekian and Wedepohl, 1961) are a fallback, not a first choice.

2.8 Petroleum pollution in the Niger Delta

Oil spills, pipeline vandalism, artisanal refining and gas flaring have contaminated soils, creeks and groundwater in parts of the Niger Delta. Geochemistry measures the extent of the damage, identifies the source and checks the success of clean-up.

What is measured:

- **Total petroleum hydrocarbons (TPH):** the total amount of oil in soil, sediment or water. Simple and widely used, but says little about toxicity.
- **BTEX** (benzene, toluene, ethylbenzene and xylenes): light, soluble and toxic compounds that reach groundwater first. Benzene causes cancer.
- **Polycyclic aromatic hydrocarbons (PAHs):** multi-ring compounds that persist in sediment and build up in shellfish such as periwinkles and oysters.
- **Heavy metals** associated with crude oil and drilling waste, including nickel, vanadium, lead and barium.

The best known study is the United Nations Environment Programme (UNEP) environmental assessment of Ogoniland, published in 2011. It found hydrocarbon contamination in soils and groundwater at many sites, in places several metres deep. At one community it found benzene in drinking water at concentrations far above the WHO guideline. The study remains a model of how sampling, laboratory analysis and geochemical interpretation support decisions on clean-up.

Oil fingerprinting. Crude oils differ in their mix of hydrocarbons and biomarkers. Gas chromatography and GC–MS compare spilled oil with candidate sources: a pipeline, a wellhead or a tanker. Ratios such as pristane/phytane and the patterns of hopanes and steranes are used (see Section 5.6). Fingerprinting is used in legal disputes over who caused a spill.

Weathering of spilled oil. Once spilled, oil changes. Light compounds evaporate and dissolve within days. Bacteria then degrade the straight-chain alkanes, leaving the branched and ring compounds. The ratio of a straight-chain alkane to a branched one, such as n-C_{17}/pristane, falls as biodegradation proceeds. This ratio can estimate how long ago a spill happened and whether natural attenuation is working.

2.9 Other environmental applications

- **Gas flaring and acid rain.** Flaring releases sulphur and nitrogen oxides and soot. Rainwater and roof-harvested water near flare sites can be more acidic and carry more metals.
- **Dumpsites and leachate.** Urban waste dumps release leachate rich in chloride, ammonium, nitrate and metals. Groundwater down the flow path shows rising EC and nitrate.
- **Pit latrines and septic tanks.** Shallow wells near latrines in delta towns often show high nitrate, chloride and faecal coliforms. Geochemistry and simple spacing rules protect water supplies.
- **Medical geology.** Natural excess or deficiency of elements affects health. Examples include fluorosis from high-fluoride groundwater, goitre in iodine-poor inland areas, and lead poisoning from artisanal gold processing in Zamfara State in 2010.

2.10 Key points of Section 2

- Check the charge balance before interpreting any water analysis.
- Facies and ratios reveal the origin of water; standards decide whether it is fit for use.
- Rising chloride, a falling HCO_3^- share and Ca–Cl facies are early warnings of saltwater intrusion.
- Contamination indices are only as reliable as the background values behind them.

Section 3: Geochemistry in mineral exploration

Geochemical exploration finds ore deposits by tracing the chemical trail they leave in rocks, soils, sediments, water and plants. An ore body is small and often hidden, but its halo of dispersed elements is much larger. Sampling that halo, then following it inward, narrows a search from thousands of square kilometres to a few drill holes. Nigeria's gold, lead–zinc, tin, tantalum and lithium deposits have all been studied this way.

3.1 The principle

An **ore deposit** is a concentration of one or more elements far above crustal abundance, rich enough to mine at a profit. Gold averages about 0.004 ppm in the crust, but a workable gold ore may carry 1 to 10 ppm. Such strong enrichment cannot form without changing the rock around it. Hydrothermal fluids alter the wall rock, and weathering later spreads the ore elements outward. Both effects create a target much larger than the ore itself.

The degree of enrichment is expressed as the **concentration factor**:

$$\text{Concentration factor} = \frac{\text{grade of ore}}{\text{average crustal abundance}} \qquad \text{for gold: } \frac{4 \text{ ppm}}{0.004 \text{ ppm}} = 1000$$

Geochemical exploration therefore looks for three things:

1. **Ore elements** themselves, such as Cu, Pb, Zn, Au or Sn.
2. **Pathfinder elements**, which travel with the ore but are easier to detect, more mobile, or form wider halos.
3. **Alteration signatures**, changes in major elements caused by the ore-forming fluids, such as added potassium or lost sodium.

3.2 Primary halos and wall-rock alteration

Primary halos form at the same time as the ore. Hot fluids rising through fractures react with the rocks they pass and leave behind a zoned pattern of added and removed elements. Primary halos can extend tens to hundreds of metres from the ore, and above it they may reach the surface even when the ore is deep.

Common alteration types and their chemistry:

Alteration	Minerals formed	Chemical change	Associated deposits
Potassic	K-feldspar, biotite	K added, Na and Ca lost	Porphyry copper core
Phyllic (sericitic)	Sericite, quartz, pyrite	K and S added; Na, Ca, Mg lost	Porphyry copper; orogenic gold
Argillic	Kaolinite, smectite	Strong loss of alkalis	Epithermal gold; outer porphyry zones
Propylitic	Chlorite, epidote, calcite	Ca and CO_2 added	Outer zone of many hydrothermal systems
Silicification	Quartz	Si added	Gold-bearing veins

Alteration	Minerals formed	Chemical change	Associated deposits
Greisenisation	Quartz, muscovite, topaz	F, Li, Sn, W added	Tin–tungsten deposits in granites
Albitisation	Albite	Na added	Rare-metal granites and pegmatites

Rock sampling of fresh and altered rock, together with drill-core sampling, maps these halos in three dimensions.

3.3 Secondary dispersion: soil anomalies

When ore weathers, its elements spread into the soil above and around it. A **soil anomaly** above an ore body is the main target of detailed geochemical exploration.

Three factors decide how useful a soil anomaly is:

- **Residual or transported soil.** A residual soil formed in place from the rock below carries an anomaly directly above the source. A transported soil (alluvium, colluvium, windblown sand) may hide the ore completely or shift the anomaly far from it.
- **Soil horizon.** Elements are not spread evenly with depth. In tropical laterites, the iron-rich duricrust and mottled zone often hold gold and pathfinder metals, while the leached pallid zone below holds little. Samplers must collect the same horizon at every site.
- **Grain size.** Metals adsorbed on clays and iron oxides concentrate in the fine fraction. Gold and tin, which travel as resistant grains, may be in the coarse fraction. Test which fraction gives the best contrast before running a full survey.

On slopes, soil creep drags the anomaly downhill, so the peak may lie downslope of the ore. This **displacement** must be allowed for when choosing drill sites.

3.4 Secondary dispersion: stream sediments

A stream drains its whole catchment. A single sediment sample near the mouth of a small stream represents every rock exposed upstream. This makes **stream sediment sampling** the standard method for regional reconnaissance.

The dispersion train in a stream decays downstream as clean sediment from other tributaries dilutes it. The useful length of a train depends on the element and the stream, and may range from a few hundred metres to several kilometres. Explorers sample at stream junctions, then walk upstream from an anomalous junction until the anomaly stops, which points to the source.

Two sample types are used together:

- **Fine fraction of active stream sediment**, usually minus 80 mesh (below 180 µm), for metals held by clays and oxides.
- **Heavy mineral concentrates**, panned from gravel, for gold, cassiterite, columbite–tantalite, scheelite and other dense, resistant minerals. Counting gold grains and noting their shape (rounded or angular) shows how far they have travelled.

Nigeria's artisanal gold and tin miners work this principle by hand. Many alluvial workings on the Jos Plateau and in the schist belts sit downstream of primary sources that were later found by tracing the heavy minerals upstream.

3.5 Pathfinder elements

A **pathfinder** is an element found with an ore that is easier to detect than the ore element itself. Pathfinders may be more abundant, more mobile, cheaper to analyse, or less affected by nugget effects.

Deposit type	Ore elements	Useful pathfinders
Orogenic (lode) gold	Au	As, Sb, W, Bi, Te, Hg, B
Porphyry copper	Cu, Mo, Au	Mo, Re, Ag, Te; Zn, Pb, Mn in the outer halo
Lead–zinc (sediment-hosted)	Pb, Zn	Cd, Ag, Ba, F, Mn
Tin–tungsten (greisen and vein)	Sn, W	F, Li, Rb, Cs, B, Mo, Bi
Rare-metal (LCT) pegmatite	Li, Ta, Cs, Sn	Rb, Cs, Be, Nb, B; low K/Rb and Nb/Ta ratios
Nickel–copper sulphide	Ni, Cu, PGE	Co, Cr, S, Pd
Uranium	U	Mo, Se, V, Rn, He

Arsenic is the classic gold pathfinder. Gold grains are rare and patchy, so two samples a metre apart may give very different gold values. Arsenic, carried in arsenopyrite, is spread far more evenly and forms a broader, steadier halo.

3.6 Stages of a geochemical exploration programme

Exploration moves from large areas with sparse samples to small areas with dense samples. Each stage tests whether the next is worth paying for.

Stage	Area covered	Usual media	Typical sample density	Purpose
Orientation survey	A known deposit or a small test area	All likely media	Dense	Choose the best medium, fraction, horizon and method
Regional reconnaissance	Hundreds to thousands of km^2	Stream sediment, heavy minerals	About 1 sample per 1 to 10 km^2	Find mineralised districts
Follow-up	Tens of km^2	Stream sediment, soil traverses, rock chips	Closer spacing upstream of anomalies	Locate the source area
Detailed survey	1 to a few km^2	Grid soil sampling, rock and trench sampling	Lines 50 to 200 m apart, samples 10 to 50 m along lines	Define drill targets
Drilling and evaluation	The prospect	Core and chips	Every metre or by geological interval	Prove grade and tonnage

The **orientation survey** is the step most often skipped and most often regretted. A short test over a known occurrence shows which approach actually works in the local soils and climate before money is spent on a whole region.

3.7 Recognising and ranking anomalies

Not every high value is ore. A sound interpretation asks:

- **Is it real?** Check QC results, repeat the analysis, and resample in the field.
- **Is it explained by rock type?** Mafic rocks naturally carry more Cu, Ni, Co and Cr than granites. Black shales carry more Mo, V, U and Zn. Compare each sample with the background of its own rock type, not a single regional value.
- **Is it explained by the environment?** Iron and manganese oxide coatings scavenge metals and create false anomalies. Swamps concentrate metals in organic matter. Ratios such as Cu/Fe or Zn/Mn reduce this effect.
- **Is it explained by contamination?** Old mine workings, roads, villages, farms using copper fungicide and scrap metal all make anomalies without ore.
- **Does it hang together?** A true anomaly usually covers several neighbouring samples, involves several associated elements, and follows a geological structure such as a shear zone or a contact.

Anomaly **contrast** is the ratio of the peak value to background:

$$\text{Contrast} = \frac{\text{peak value}}{\text{background}}$$

High contrast with a coherent shape and a sensible multi-element signature gives a high-priority target. In the Section 1.11 example, the 95 ppm Cu sample has a contrast of 95/20, or about 4.8.

3.8 Other exploration media

- **Biogeochemistry.** Deep-rooted trees draw elements from below a transported cover. Sampling the same species and the same part (bark, twigs or leaves) can reveal ore under sand or alluvium.
- **Geobotany.** Some plants grow only on metal-rich soils, or show stunting and colour changes there. These **indicator plants** have guided prospectors to copper deposits in Central Africa.
- **Hydrogeochemistry.** Groundwater and springs that pass through ore carry dissolved metals and sulphate. Useful in deeply weathered or covered terrain.
- **Soil gas and partial extractions.** Mercury vapour, radon, CO_2 and weak-leach methods that measure only the most mobile metals can detect ore beneath tens of metres of cover.
- **Lithogeochemistry and indicator ratios.** In pegmatite exploration, ratios in K-feldspar and muscovite, such as K/Rb and Nb/Ta, show how far the melt fractionated. Low values point toward the most evolved, lithium- and tantalum-rich pegmatites.

3.9 Marine mineral exploration

Marine geologists apply the same methods offshore, with sediment grabs, cores and seabed imaging in place of soil pits. Targets include:

- **Heavy mineral placers** on beaches and the shallow shelf: ilmenite, rutile, zircon, monazite and gold, concentrated by waves and currents.
- **Phosphorites** on continental margins where upwelling supplies nutrients.
- **Manganese nodules** on the deep ocean floor, rich in Mn, Ni, Cu and Co.
- **Cobalt-rich crusts** on seamount slopes.

- **Seafloor massive sulphides** at spreading ridges, rich in Cu, Zn, Pb, Au and Ag.
- **Aggregate sand and gravel** for construction and land reclamation, already dredged along the Nigerian coast.

Geochemistry of seabed sediments also sets the environmental baseline that any marine mining licence requires.

3.10 Nigerian examples

Region	Commodity	Geological setting	Geochemical approach
Schist belts of the north-west and south-west (for example Anka, Maru, Ilesha areas)	Gold	Orogenic lode gold in shear zones	Stream sediment and heavy minerals; soil As and Au; rock chips from quartz veins
Benue Trough (for example Abakaliki, Ishiagu areas)	Lead, zinc, barite	Sediment-hosted veins in Cretaceous rocks	Soil and stream Pb, Zn, Cd, Ba along fracture trends
Jos Plateau Younger Granites	Tin, columbite	Greisens and albitised granites; alluvial placers	Heavy minerals; F, Li, Rb, Sn in granites
Pegmatite fields of the basement (for example Nasarawa, Kwara, Oyo, Ekiti and Kaduna areas)	Lithium, tantalum, tin	Rare-metal LCT pegmatites	K/Rb and Nb/Ta in feldspar and mica; Li, Cs, Ta in soil and rock
Coastal sands of the Niger Delta and western coast	Heavy minerals, silica sand	Beach and shelf placers	Heavy-mineral separation and mineral chemistry

3.11 Key points of Section 3

- An ore body leaves a chemical halo much larger than itself; exploration follows the halo inward.
- Stream sediments search regions; soils and rocks pinpoint targets.
- Pathfinders and multi-element patterns give clearer signals than the ore element alone.
- Every anomaly must be tested against rock type, scavenging and contamination before drilling.

Section 4: Geochemistry in engineering geology

The chemistry of ground and groundwater decides how long a structure lasts. Soils and waters rich in sulphate, chloride or acid attack concrete and steel. Clay minerals decide whether a soil swells, shrinks or disperses. Weathering weakens rock long before it looks decayed. For coastal works in the Niger Delta, where foundations sit in saline, organic and sulphur-rich ground, chemical testing is as important as strength testing.

4.1 Why chemistry matters to the engineering geologist

Most engineering geology describes the ground in physical terms: strength, stiffness, permeability and grading. Chemistry adds three questions that physical tests cannot answer:

1. **Will the ground change?** Weathering, swelling clays and oxidising pyrite change soil and rock properties during the life of a structure.
2. **Will the ground attack the structure?** Sulphate, chloride, acid and bacteria degrade concrete, steel reinforcement and buried pipes.
3. **Will the construction materials last?** Aggregates and mixing water can carry salts or reactive minerals that damage concrete from within.

A site investigation report for any structure in contact with ground or water should therefore include a chemical test schedule.

4.2 Chemical weathering and rock strength

Weathering converts strong, interlocked minerals into weaker clays and oxides. Feldspars alter to kaolinite, biotite to vermiculite and kaolinite, and ferromagnesian minerals to clay and iron oxide. Mobile elements (Ca, Na, K, Mg) are leached; immobile ones (Al, Ti, Fe, Zr) stay behind.

The weathering of feldspar to kaolinite shows the process:

$$2\,KAlSi_3O_8 + 2\,H^+ + 9\,H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2\,K^+ + 4\,H_4SiO_4$$

Chemical weathering indices measure this change. The most widely used is the **Chemical Index of Alteration (CIA)** of Nesbitt and Young (1982), calculated from molar proportions of the oxides:

$$\text{CIA} = \frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O + K_2O} \times 100$$

CaO* is the calcium held in silicate minerals only, excluding carbonate and apatite. Fresh granite gives a CIA of about 45 to 55. Strongly weathered material approaches 100 as the alkalis and calcium are lost.

CIA and similar indices correlate with engineering behaviour. As CIA rises, density and strength fall, while porosity, water absorption and clay content rise. A rock that looks sound in an outcrop but has a high CIA may fail as an aggregate or a foundation.

4.3 Clay minerals and soil behaviour

Clay mineralogy controls plasticity, swelling, shrinkage and permeability. The three main groups behave very differently.

Clay group	Structure	Cation exchange capacity (meq/100 g, approximate)	Engineering behaviour
Kaolinite	1:1 layers, tightly bonded	3 to 15	Low plasticity, low swelling; generally stable
Illite	2:1 layers held by potassium	10 to 40	Moderate plasticity and swelling
Smectite (montmorillonite)	2:1 layers with water and exchangeable cations between them	80 to 150	High plasticity; large swelling and shrinkage; low strength when wet

Cation exchange capacity (CEC) measures how many exchangeable cations a soil can hold. It is a quick chemical guide to clay type: a high CEC points to smectite and to swelling problems.

Expansive soils rich in smectite crack light buildings, roads and canal linings as they swell in the rains and shrink in the dry season. In Nigeria, the black cotton soils of the north-east (for example around Maiduguri) are the best known. Smaller pockets of smectite-rich clay occur in Cretaceous and Tertiary shales in the south.

The exchangeable cation also matters. A smectite saturated with sodium swells and disperses far more than one saturated with calcium. This is why chemical treatment with lime (adding calcium) is an effective way to stabilise expansive clays.

4.4 Lateritic soils

Laterites and lateritic soils form under hot, wet tropical weathering. Silica is leached and iron and aluminium oxides concentrate. They are used widely in Nigeria as road base, fill and building material.

The **silica–sesquioxide ratio** is the classic chemical test for laterite:

$$\mathrm{S/R} = \frac{\mathrm{SiO_2}}{\mathrm{Fe_2O_3} + \mathrm{Al_2O_3}}$$

Calculated from molar proportions, a ratio below 1.33 indicates a true laterite, 1.33 to 2.0 a lateritic soil, and above 2.0 a non-lateritic tropical soil. Lower ratios generally mean better-cemented, more durable material.

Good laterite gravel makes excellent road base. Poor laterite, rich in kaolinite and halloysite or derived from mica-rich rock, loses strength when wet. Chemical and mineralogical tests (S/R ratio, XRD, CEC) help separate the two before a borrow pit is opened.

4.5 Dispersive soils

Dispersive soils are clays that break down into single particles in still water. Rainwater and seepage carry the particles away, opening tunnels and gullies. Dispersive clays have caused failures of earth dams, embankments and road shoulders worldwide.

Dispersion is a chemical property. It happens when sodium dominates the exchange sites on the clay. Two common measures are:

Exchangeable sodium percentage (ESP): exchangeable sodium as a percentage of the CEC. An ESP above about 15 suggests a dispersive soil; values between about 6 and 15 call for caution.

$$\text{ESP} = \frac{\text{exchangeable Na}^{+}}{\text{CEC}} \times 100$$

Sodium adsorption ratio (SAR): calculated from the pore water or a soil extract, with concentrations in meq/L.

$$\text{SAR} = \frac{\text{Na}^{+}}{\sqrt{(\text{Ca}^{2+} + \text{Mg}^{2+})/2}}$$

Worked example. A soil extract contains 12 meq/L Na^{+}, 2 meq/L Ca^{2+} and 2 meq/L Mg^{2+}.

$$\text{SAR} = \frac{12}{\sqrt{(2+2)/2}} = \frac{12}{\sqrt{2}} = \frac{12}{1.41} \approx 8.5$$

This is a moderately high value, and the soil should be checked with physical dispersion tests (crumb test, double hydrometer test and pinhole test) before it is used in an embankment.

SAR is also used to judge irrigation water, because high-sodium water destroys soil structure on farmland.

4.6 Sulphate attack on concrete

Sulphate in soil or groundwater reacts with the hardened cement paste in concrete. It forms ettringite and gypsum, which occupy more volume than the minerals they replace. The concrete expands, cracks and loses strength from the surface inward. Under cool, wet conditions with carbonate present, sulphate can also form thaumasite, which turns the paste to a soft mush.

The first step is the formation of gypsum from portlandite (calcium hydroxide) in the cement paste:

$$\text{Ca(OH)}_2 + \text{SO}_4^{2-} + 2\,\text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + 2\,\text{OH}^{-}$$

Sources of sulphate in the ground include:

- **Seawater and brackish creek water**, with about 2,700 mg/L sulphate in full-strength seawater.
- **Oxidation of pyrite** in marine clays, shales and dredged mangrove mud (Section 4.8).
- **Gypsum** in evaporitic soils and some sedimentary rocks.
- **Industrial waste and fill**, including slag and demolition rubble.

Design codes set exposure classes from the measured sulphate. The table follows the classes in ACI 318 (American Concrete Institute); British practice uses the similar BRE Special Digest 1 system. Confirm the edition used by your project.

Exposure class	Water-soluble sulphate in soil (% by mass)	Sulphate in water (mg/L)	Typical requirement
S0 (negligible)	Below 0.10	Below 150	No special cement

Exposure class	Water-soluble sulphate in soil (% by mass)	Sulphate in water (mg/L)	Typical requirement
S1 (moderate)	0.10 to 0.20	150 to 1,500, and seawater	Moderate sulphate-resisting cement; limited water–cement ratio
S2 (severe)	0.20 to 2.00	1,500 to 10,000	High sulphate-resisting cement; lower water–cement ratio
S3 (very severe)	Above 2.00	Above 10,000	High sulphate-resisting cement with pozzolan or slag; strict limits

Dense, well-compacted, low water–cement ratio concrete is the first defence. Sulphate-resisting cement, fly ash, slag and protective coatings add further protection.

4.7 Chloride and corrosion of steel

Steel reinforcement in concrete is normally protected by a thin passive film, kept stable by the high pH (about 12.5 to 13.5) of the cement paste. Chloride ions break this film. Once enough chloride reaches the steel, corrosion begins. Rust occupies several times the volume of the original steel, so the concrete cover cracks and spalls.

A chloride content at the steel of about 0.2 to 0.4% by mass of cement is commonly taken as the threshold for corrosion to start. Marine structures in the **splash and tidal zones** are most at risk, because repeated wetting and drying draws chloride inward and supplies the oxygen and moisture that corrosion needs.

Carbonation is a second cause. Carbon dioxide from the air reacts with the cement paste and lowers its pH below about 9, removing the protection even without chloride:

$$\mathrm{Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O}$$

Depth of carbonation is tested by spraying a fresh broken surface with phenolphthalein, which stays colourless where the concrete has carbonated.

Jetties, bridges, sea walls and buildings along the creeks of Delta, Rivers and Bayelsa States face both threats. Good practice is to measure chloride and sulphate in groundwater and creek water at design stage, specify enough concrete cover, and test existing structures for chloride profile and carbonation depth.

4.8 Acid sulphate soils

Mangrove and tidal-flat muds of the Niger Delta and the Lagos lagoon contain fine-grained pyrite, formed when sulphate-reducing bacteria act on seawater sulphate in organic mud. While the mud stays waterlogged, the pyrite is stable. Once it is drained, dredged or excavated, air reaches the pyrite and it oxidises:

$$\mathrm{FeS_2 + 15/4\ O_2 + 7/2\ H_2O \rightarrow Fe(OH)_3 + 2\,SO_4^{2-} + 4\,H^+}$$

Each mole of pyrite releases four moles of acid and two of sulphate. Soil pH can fall below 4, and in severe cases below 3. Such soils are called **acid sulphate soils**. In the field they show pale yellow jarosite mottles, rusty iron staining and dead vegetation.

Engineering consequences:

- Severe sulphate and acid attack on concrete piles, culverts and foundations.
- Rapid corrosion of steel sheet piles and buried pipelines.
- Release of aluminium, iron and heavy metals into drainage water, killing fish in creeks.
- Settlement as organic and sulphide-rich mud consolidates and oxidises.

Simple tests detect them. The **field peroxide test** adds hydrogen peroxide to a soil sample: a strong fizz and a pH drop below about 3 suggests oxidisable sulphide. Laboratory tests measure total sulphur, chromium-reducible sulphur and acid–base balance. Land reclamation, sand-filling over mangrove swamp and canal dredging in the delta all need this testing.

4.9 Corrosivity of soil to buried steel

Pipelines, piles, cables and tanks buried in the ground corrode at rates set largely by soil chemistry. The main factors are:

- **Electrical resistivity:** low resistivity means more dissolved salts and faster corrosion.
- **pH:** acid soils corrode steel faster.
- **Redox potential:** low-redox, waterlogged soils favour sulphate-reducing bacteria, which cause rapid pitting.
- **Chloride and sulphate content.**
- **Moisture and aeration differences** along a pipe, which set up corrosion cells.

As a rough guide, soils with resistivity below about 1,000 Ω·cm are very corrosive, 1,000 to 5,000 Ω·cm corrosive to moderately corrosive, and above 10,000 Ω·cm only mildly corrosive. Saline, organic delta soils often fall in the very corrosive range. Pipeline engineers respond with coatings and cathodic protection.

4.10 Construction materials

Aggregates. Some aggregates contain reactive silica, such as chert, opal, chalcedony or strained quartz. In concrete, this silica reacts with alkalis from the cement in the **alkali–silica reaction (ASR)**, forming a gel that swells and cracks the concrete. Petrographic examination and chemical tests screen aggregates before use.

Sea-dredged and creek sand. Sand dredged from the sea, lagoons and creeks is widely used in the Niger Delta and Lagos. Unwashed, it carries chloride that later corrodes reinforcement, and shell fragments that weaken the mix. Chloride testing and thorough washing with fresh water are essential.

Mixing water. Water for concrete should be clean and fit to drink where possible. Brackish borehole or creek water adds chloride and sulphate. Test it against the limits in the concrete standard used on the project.

Building stone. Rocks with swelling clays, pyrite or soluble salts weather quickly in walls and facings. Pyrite oxidation causes rust stains and expansion.

4.11 A chemical test schedule for a coastal site

For a jetty, bridge or building on a delta or coastal site, a basic chemical test schedule includes:

- pH, EC and chloride of groundwater and creek water
- Water-soluble and acid-soluble sulphate in soil

- Total sulphur and the peroxide test for acid sulphate potential
- Organic matter content of soils
- Soil resistivity and redox potential for buried steel
- Clay mineralogy and CEC where swelling or dispersion is possible
- Chloride and shell content of fill and concrete sand

4.12 Key points of Section 4

- Weathering indices such as CIA and the S/R ratio turn chemistry into an estimate of rock and soil quality.
- Smectite, sodium and high CEC mean swelling and dispersion problems.
- Sulphate attacks concrete; chloride and carbonation attack the steel inside it.
- Disturbing pyritic mangrove mud creates acid sulphate soils, a major hazard for coastal works in the Niger Delta.

Section 5: Geochemistry in petroleum exploration

Petroleum geochemistry asks whether a basin has rocks able to generate oil or gas, whether they have been heated enough to do so, and where the generated fluids went. It reduces the risk of drilling dry holes and explains the oils already found. The Niger Delta, Nigeria's main petroleum province, is a classic case for each of these questions.

5.1 The petroleum system

A **petroleum system** is the set of geological elements and processes needed for oil and gas to accumulate. The elements are:

- **Source rock:** a fine-grained rock rich in organic matter, usually shale or marl, that generates petroleum when heated.
- **Reservoir rock:** a porous, permeable rock, usually sandstone or carbonate, that holds the petroleum.
- **Seal (cap rock):** an impermeable layer, usually shale or evaporite, that stops petroleum escaping upward.
- **Overburden:** the sediments that bury the source rock deeply enough to heat it.

The processes are trap formation, generation, migration and accumulation, and they must occur in the right order. A trap that forms after oil has migrated past it will stay empty. Geochemistry deals mainly with the source rock, generation, migration and the nature of the oil itself.

5.2 Organic matter and kerogen

Organic matter that survives burial in fine sediment is converted, over time, into **kerogen**: the insoluble organic material in sedimentary rocks. A smaller fraction, soluble in organic solvents, is called **bitumen**. Kerogen is the true source of most petroleum.

Preservation of organic matter needs low oxygen at the sea or lake floor, rapid burial, or high productivity in the water above. Oxygen-poor bottom waters in restricted basins, upwelling margins and deltas with high sediment and plant input favour rich source rocks.

Kerogen is classified into four types by its origin and its hydrogen content:

Kerogen type	Main origin	Hydrogen content	Main product
Type I	Lacustrine algae	Very high	Oil, often waxy
Type II	Marine plankton and bacteria	High	Oil and gas
Type II-S	Marine, sulphur-rich	High	Heavy, high-sulphur oil generated early
Type III	Land plants (woody and herbaceous material)	Low	Mainly gas, some waxy oil
Type IV	Reworked or oxidised material, charcoal	Very low	Little or none (inert)

The **van Krevelen diagram** plots the atomic H/C ratio against the O/C ratio, or its Rock-Eval equivalent, the hydrogen index (HI) against the oxygen index (OI). Each kerogen type follows its

own curve. As kerogen matures, it loses hydrogen and oxygen and all curves converge toward the origin.

5.3 Source rock evaluation: quantity

The first test of a source rock is **total organic carbon (TOC)**, the weight percentage of organic carbon in the rock. Samples are first treated with acid to remove carbonate carbon, then burned, and the CO_2 released is measured.

Widely used guidelines for shale source rocks (after Peters and Cassa, 1994):

TOC (wt%)	Source rock quality
Below 0.5	Poor
0.5 to 1.0	Fair
1.0 to 2.0	Good
2.0 to 4.0	Very good
Above 4.0	Excellent

TOC alone is not enough. A rock rich in inert Type IV carbon may have a high TOC but cannot generate petroleum. Kerogen quality must be tested too.

5.4 Source rock evaluation: Rock-Eval pyrolysis

Rock-Eval pyrolysis heats a small sample of powdered rock in an inert atmosphere, in a programmed temperature ramp, and measures what is released. It is the workhorse of source rock screening.

Parameter	Unit	Meaning
S_1	mg HC/g rock	Free hydrocarbons already present in the rock, released at low temperature
S_2	mg HC/g rock	Hydrocarbons generated by cracking the kerogen; the remaining generation potential
S_3	mg CO_2/g rock	CO_2 from oxygen-bearing organic matter
T_{max}	°C	Temperature at which S_2 peaks; rises with maturity

From these, three indices follow. HI is the **hydrogen index** in mg HC/g TOC, OI is the **oxygen index** in mg CO_2/g TOC, and PI is the **production index**:

$$\text{HI} = \frac{S_2 \times 100}{\text{TOC}}$$

$$\text{OI} = \frac{S_3 \times 100}{\text{TOC}}$$

$$\text{PI} = \frac{S_1}{S_1 + S_2}$$

HI indicates kerogen type in immature rocks:

HI (mg HC/g TOC)	Kerogen type	Expected product
Above 600	Type I	Oil
300 to 600	Type II	Oil
200 to 300	Mixed Type II and III	Oil and gas
50 to 200	Type III	Gas, minor oil
Below 50	Type IV	None

The S_2 value also grades **generation potential**: below 2.5 mg HC/g rock is poor, 2.5 to 5 fair, 5 to 10 good, and above 10 very good.

Worked example. A shale from a delta well gives TOC = 2.4 wt%, S_1 = 0.6 mg/g, S_2 = 6.0 mg/g, S_3 = 1.2 mg/g and T_{max} = 438 °C.

$$\text{HI} = \frac{6.0 \times 100}{2.4} = 250 \text{ mg HC/g TOC}$$

$$\text{OI} = \frac{1.2 \times 100}{2.4} = 50 \text{ mg } CO_2\text{/g TOC}$$

$$\text{PI} = \frac{0.6}{0.6 + 6.0} = 0.09$$

Interpretation:

- HI of 250 means mixed Type II–III kerogen.
- TOC of 2.4% is very good; S_2 of 6.0 is good potential.
- T_{max} of 438 °C and PI of 0.09 mean early maturity (next subsection).

Conclusion: a good source rock for oil and gas, just entering the oil window.

5.5 Source rock evaluation: maturity

Kerogen generates petroleum only when heated enough. As burial deepens, temperature rises along the geothermal gradient:

$$T_z = T_0 + G \times z$$

Here T_z is the temperature at depth z, T_0 is the surface temperature and G is the geothermal gradient. With a surface temperature of 27 °C and a gradient of 25 °C/km, a shale at 3 km is at about 27 + 25 × 3 = 102 °C. The kerogen passes through stages:

- **Diagenesis:** shallow and cool; biogenic methane forms; little oil.
- **Catagenesis:** the **oil window**, roughly 60 to 120 °C depending on heating rate and kerogen type; oil and wet gas are generated, followed by gas as temperature rises.
- **Metagenesis:** above about 150 to 200 °C; only dry methane is generated; oil is cracked to gas.

Three common maturity measures, with commonly used boundaries (after Peters and Cassa, 1994):

Stage	Vitrinite reflectance, R_o (%)	Rock-Eval T_{max} (°C)	Production index
Immature	Below 0.6	Below 435	Below 0.10
Early oil window	0.6 to 0.65	435 to 445	0.10 to 0.15
Peak oil window	0.65 to 0.9	445 to 450	0.25 to 0.40
Late oil window	0.9 to 1.35	450 to 470	Above 0.40
Gas window (postmature)	Above 1.35	Above 470	Not meaningful

Vitrinite reflectance is measured under a reflected-light microscope on vitrinite, a coal maceral from woody tissue. Its reflectance rises steadily and irreversibly with temperature. Your optical mineralogy skills from other courses carry over directly to this method.

Basin modelling combines maturity data with burial history and heat flow to predict when and where a source rock entered the oil window. This timing must fit the age of the traps.

5.6 Oil composition and biomarkers

Crude oil is a mixture of thousands of compounds. They are grouped into saturated hydrocarbons, aromatic hydrocarbons, resins and asphaltenes, known together as **SARA** fractions. Bulk properties include API gravity, sulphur content and wax content. API gravity is calculated from the specific gravity (SG) of the oil at 60 °F:

$$°\text{API} = \frac{141.5}{\text{SG}} - 131.5$$

Lighter oils have higher API gravity. Water has an API gravity of 10, so oils with API above 10 float on water.

Biomarkers (biological markers) are molecules in oil and rock extracts whose carbon skeletons can be traced back to specific living organisms. They survive burial with little change, so they record the source of the organic matter, the environment of deposition and the maturity. They are measured by GC–MS.

Biomarker or ratio	What it indicates
Pristane/phytane (Pr/Ph)	Redox of the depositional setting: above about 3 suggests oxic, land-plant-rich settings; below about 1 suggests anoxic, often marine or saline settings
n-alkane distribution and carbon preference index (CPI)	Land-plant waxes give long-chain alkanes with odd-carbon preference; CPI near 1 means mature
Oleanane	Flowering plants (angiosperms); indicates a source no older than Late Cretaceous, typical of Tertiary deltas
C_{27}, C_{28} and C_{29} regular steranes	Relative input of marine algae (C_{27}) and land plants (C_{29})
Hopanes	Bacterial input; also used for maturity and biodegradation
Ts/Tm and sterane 20S/(20S + 20R)	Maturity
Gammacerane	Stratified, often saline water column

Oil–source correlation compares the biomarker fingerprint of an oil with extracts from candidate source rocks. A match tells explorers which rock charged a field, which guides the search for more fields from the same source. **Oil–oil correlation** groups oils into families from the same source.

5.7 Alteration of oil in the reservoir

Oil can change after it reaches a trap:

- **Biodegradation:** in reservoirs cooler than about 80 °C, bacteria consume n-alkanes first, then branched alkanes, then steranes and hopanes. The oil becomes heavier, more viscous and lower in value. Many shallow reservoirs in the Niger Delta contain biodegraded oils.
- **Water washing:** moving formation water removes the more soluble light aromatic compounds.
- **Thermal cracking:** in deep, hot reservoirs, oil cracks to gas and condensate.
- **Gas deasphalting:** gas entering an oil reservoir can precipitate asphaltenes.

Recognising these changes avoids false correlations and helps predict oil quality before drilling.

5.8 Natural gas geochemistry

Gas composition and carbon isotopes reveal its origin. **Dry gas** is almost pure methane. **Wet gas** contains significant ethane, propane and butane. Gas wetness is expressed as:

$$\text{Wetness (\%)} = \frac{C_2 + C_3 + C_4 + C_5}{C_1 + C_2 + C_3 + C_4 + C_5} \times 100$$

Here C_1 is methane, C_2 ethane, and so on.

The carbon isotope ratio of methane is written $\delta^{13}C$ and reported in parts per thousand (‰) relative to the VPDB standard:

$$\delta^{13}\text{C} = \left(\frac{(^{13}\text{C}/^{12}\text{C})_{\text{sample}}}{(^{13}\text{C}/^{12}\text{C})_{\text{standard}}} - 1 \right) \times 1000$$

It separates two main sources:

- **Biogenic (microbial) methane:** very light, generally more negative than about −60‰, and very dry. Formed by bacteria at shallow depth.
- **Thermogenic methane:** heavier, generally about −50‰ to −30‰, often with wet components. Formed by cracking of kerogen and oil at depth.

This matters in the Niger Delta, where both shallow biogenic gas and deep thermogenic gas occur.

5.9 Surface geochemical prospecting

No seal is perfect. Small amounts of hydrocarbon leak upward from most accumulations. **Macroseeps** are visible oil and gas seeps. **Microseeps** are invisible traces detectable only by sensitive analysis. Surface geochemical prospecting maps these traces to find buried fields.

Methods include:

- **Soil gas surveys:** light hydrocarbons (methane to pentane) collected from shallow probes. Elevated wet-gas ratios suggest thermogenic leakage.

- **Headspace and adsorbed gas:** hydrocarbons trapped in soil or sediment, released in the laboratory.
- **Marine seabed sampling:** piston cores and grabs analysed for hydrocarbons and biomarkers, often guided by seabed imaging of pockmarks, mud volcanoes and seep sites.
- **Induced surface changes:** seeping hydrocarbons create reducing conditions above a field. These can cause carbonate cementation, bleaching of red beds, magnetic minerals and changes in soil microbes.

Surface surveys cannot measure depth or size. They are best used with seismic data to rank prospects that seismic has already identified.

5.10 The Niger Delta petroleum system

The Niger Delta has one of the most productive Tertiary petroleum systems in the world. It is usually described in three formations, from bottom to top:

Formation	Lithology	Role in the petroleum system
Akata Formation	Marine shale, often overpressured, with turbidite sands	Main source rock candidate; also reservoirs in deep water
Agbada Formation	Alternating sandstones and shales of the delta front	Main reservoir; its shales act as seals and as a source
Benin Formation	Continental sands and gravels	Overburden; main freshwater aquifer (Section 2)

The organic matter in the delta source rocks is largely terrestrial, from land plants carried by the Niger and Benue rivers, mixed with some marine material. It is generally Type III to mixed Type II–III kerogen. The oils are characteristically low in sulphur, often waxy, with relatively high Pr/Ph ratios and abundant oleanane, which confirms an angiosperm-rich Tertiary source.

Researchers still debate the relative contributions of the Akata shales and the lower Agbada shales to the oils. Biomarker and maturity studies are the main tools in that debate. Growth faults and rollover anticlines form most traps, and the timing of fault growth against oil generation controls which structures filled.

5.11 Key points of Section 5

- A source rock needs enough organic matter (TOC), the right kind (HI and kerogen type), and enough heat (R_o and T_{max}).
- Rock-Eval gives quantity, quality and maturity from one quick analysis.
- Biomarkers link oils to sources and reveal depositional environment, maturity and biodegradation.
- Niger Delta oils are low-sulphur, oleanane-rich oils from mainly terrestrial Tertiary organic matter.

Summary, review questions and glossary

Summary

The four applications in this note share one method. Define background, find what departs from it, and explain the departure using what you know about how elements behave at the Earth's surface.

Application	Main question	Key media	Key tools and indices
Environmental and groundwater	Is the water or soil safe, and where did its chemistry come from?	Groundwater, surface water, soil, sediment	Charge balance, facies and Piper diagram, NSDWQ limits, Revelle ratio, CF, I_{geo}, EF, PLI, TPH, BTEX, PAHs
Mineral exploration	Where is the ore?	Stream sediment, heavy minerals, soil, rock	Threshold, pathfinders, dispersion halos and trains, alteration, K/Rb and Nb/Ta
Engineering geology	Will the ground change, or attack the structure?	Soil, groundwater, rock, aggregate	CIA, S/R ratio, CEC, ESP and SAR, sulphate and chloride classes, peroxide test, resistivity
Petroleum exploration	Can this basin generate and hold petroleum, and where did the oil come from?	Cuttings, cores, oils, gases, seabed sediment	TOC, Rock-Eval (HI, OI, PI, T_{max}), R_o, biomarkers, $\delta^{13}C$ of methane

Summary of key equations

Quantity	Equation	Section
pH	$\mathrm{pH} = -\log_{10} a_{\mathrm{H}^+}$	1.5
Threshold	$T = \bar{x} + 2s$ (on log-transformed data)	1.11
Milliequivalents	$\mathrm{meq/L} = \dfrac{\mathrm{mg/L} \times \mathrm{charge}}{\mathrm{atomic\ or\ formula\ weight}}$	2.3
Charge balance error	$\mathrm{CBE}\ (\%) = \dfrac{\sum \mathrm{cations} - \sum \mathrm{anions}}{\sum \mathrm{cations} + \sum \mathrm{anions}} \times 100$	2.3
Ghyben–Herzberg	$z = \dfrac{\rho_f}{\rho_s - \rho_f}\, h \approx 40\, h$	2.6
Contamination factor	$\mathrm{CF} = C_{\mathrm{sample}} / C_{\mathrm{background}}$	2.7
Geoaccumulation index	$I_{\mathrm{geo}} = \log_2 (C_n / 1.5\, B_n)$	2.7
Enrichment factor	$\mathrm{EF} = \dfrac{(C_{\mathrm{metal}}/C_{\mathrm{Al}})_{\mathrm{sample}}}{(C_{\mathrm{metal}}/C_{\mathrm{Al}})_{\mathrm{background}}}$	2.7
Pollution load index	$\mathrm{PLI} = (\mathrm{CF}_1 \times \mathrm{CF}_2 \times \cdots \times \mathrm{CF}_n)^{1/n}$	2.7

Quantity	Equation	Section
Chemical Index of Alteration	$\mathrm{CIA} = \dfrac{\mathrm{Al_2O_3}}{\mathrm{Al_2O_3} + \mathrm{CaO^*} + \mathrm{Na_2O} + \mathrm{K_2O}} \times 100$	4.2
Silica–sesquioxide ratio	$\mathrm{S/R} = \mathrm{SiO_2}/(\mathrm{Fe_2O_3} + \mathrm{Al_2O_3})$	4.4
Sodium adsorption ratio	$\mathrm{SAR} = \dfrac{\mathrm{Na^+}}{\sqrt{(\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}})/2}}$	4.5
Hydrogen index	$\mathrm{HI} = S_2 \times 100/\mathrm{TOC}$	5.4
Oxygen index	$\mathrm{OI} = S_3 \times 100/\mathrm{TOC}$	5.4
Production index	$\mathrm{PI} = S_1/(S_1 + S_2)$	5.4
API gravity	$°\mathrm{API} = 141.5/\mathrm{SG} - 131.5$	5.6

Review questions

Part A: Short answers

1. Define background, threshold and anomaly, and explain how they are related.
2. Distinguish between the primary and secondary geochemical environments, with one process typical of each.
3. Name the five Goldschmidt groups and give two elements in each.
4. Explain why iron is mobile in swamp groundwater but immobile in river water. Refer to Eh and pH.
5. Why are iron and manganese oxides important in both exploration and pollution studies?
6. List four types of quality control sample and state what each one checks.
7. Explain the difference between accuracy and precision with an example.
8. What is a hydrochemical facies? State the likely meaning of a Ca–Cl facies in a coastal aquifer.
9. Give four geochemical indicators of saltwater intrusion.
10. Why is the enrichment factor normalised to aluminium or iron?
11. What is a pathfinder element? Explain why arsenic is used in gold exploration.
12. Why must an orientation survey come before a regional geochemical survey?
13. List three causes of a false geochemical anomaly.
14. Explain how smectite and sodium together cause engineering problems.
15. Describe the chemistry of sulphate attack on concrete.
16. How do acid sulphate soils form, and why are they a hazard in the Niger Delta?
17. Explain how chloride and carbonation cause corrosion of steel in concrete.
18. Name the four kerogen types and the main product of each.
19. What do the Rock-Eval parameters S_1, S_2, S_3 and T_{max} measure?
20. What does oleanane in an oil tell you about its source?

Part B: Calculations

21. A water sample contains 23 mg/L Na^+ (atomic weight 22.99) and 71 mg/L Cl^- (atomic weight 35.45). Convert both to meq/L and calculate the Na/Cl ratio. Is this ratio closer to seawater or to fresh weathering water?
22. A water analysis gives total cations of 4.6 meq/L and total anions of 4.2 meq/L. Calculate the charge balance error and state whether the analysis is acceptable.
23. The water table in a coastal town stands 1.5 m above sea level. Use the Ghyben–Herzberg relation to estimate the depth of the fresh–salt interface. What happens to the interface if pumping lowers the water table by 0.5 m?
24. A creek sediment contains 90 mg/kg zinc. The background for zinc is 30 mg/kg. Calculate the contamination factor and the geoaccumulation index, and classify the sediment by each.
25. The $\log_{10}$ values of lead in 40 soil samples have a mean of 1.15 and a standard deviation of 0.20. Calculate the threshold in ppm.
26. A soil extract contains 18 meq/L Na^+, 3 meq/L Ca^{2+} and 5 meq/L Mg^{2+}. Calculate the SAR and comment on the dispersion risk.
27. A shale has TOC = 1.6 wt%, S_1 = 0.3 mg/g, S_2 = 2.4 mg/g, S_3 = 1.6 mg/g and T_{max} = 432 °C. Calculate HI, OI and PI. Classify the kerogen type, the generation potential and the maturity.

Part C: Essay questions

28. With examples from the Niger Delta, discuss how geochemistry is used to assess the effects of oil pollution on soil, sediment and groundwater.
29. Describe the stages of a geochemical exploration programme for rare-metal pegmatites in the Nigerian basement, from orientation survey to drilling.
30. You are the engineering geologist for a new jetty on a mangrove creek near Okerenkoko. Describe the geochemical tests you would specify, and explain why each is needed.
31. Discuss the geochemical evidence for the source, maturity and alteration of Niger Delta crude oils.

Glossary

Term	Meaning
Acid sulphate soil	Soil that produces sulphuric acid when its pyrite is exposed to air
Adsorption	Holding of ions on the surface of a solid such as clay or iron oxide
Anomaly	A concentration clearly different from background that needs explanation
Background	The normal concentration of an element in a given material and area
Biomarker	A molecule in oil or rock whose structure records the organisms it came from
Carbonation	Reaction of CO_2 with cement paste that lowers its pH and exposes steel to corrosion
Cation exchange capacity (CEC)	The amount of exchangeable cations a soil or clay can hold
Chemical Index of Alteration (CIA)	An index of chemical weathering based on loss of Ca, Na and K relative to Al

Term	Meaning
Complexing	Combination of a metal ion with another ion or molecule, often increasing its solubility
Dispersion (geochemical)	The movement of elements away from their source
Dispersive soil	A clay that breaks down into single particles in still water, usually due to high sodium
Eh	Redox potential; a measure of how oxidising or reducing a setting is
Enrichment factor (EF)	Ratio of metal to a reference element in a sample, divided by the same ratio in background
Ettringite	A calcium sulphoaluminate mineral whose growth expands and cracks concrete in sulphate attack
Facies (hydrochemical)	A water type named by its dominant cation and anion
Geoaccumulation index (I_{geo})	A log-based index of sediment contamination relative to background
Halo	The zone of dispersed elements around a source
Hydrogen index (HI)	Rock-Eval S_2 normalised to TOC; indicates kerogen type
Kerogen	Insoluble organic matter in sedimentary rocks; the main source of petroleum
Laterite	A highly weathered tropical soil rich in iron and aluminium oxides
Mobility	The ease with which an element moves in the surface environment
Oil window	The temperature range in which kerogen generates oil, roughly 60 to 120 °C
Oleanane	A biomarker from flowering plants, typical of Late Cretaceous and younger oils
Pathfinder	An element associated with an ore that is easier to detect than the ore element
Petroleum system	The source, reservoir, seal and overburden, with the processes that form an accumulation
pH	A measure of acidity, the negative log of hydrogen-ion activity
Pristane/phytane ratio	A biomarker ratio indicating the redox conditions of the source environment
Rock-Eval pyrolysis	A laboratory test that heats rock to measure its petroleum potential and maturity
Saltwater intrusion	Movement of seawater into a fresh aquifer
Sodium adsorption ratio (SAR)	A measure of sodium relative to calcium and magnesium in water
Threshold	The upper limit of normal background variation
Total organic carbon (TOC)	The weight percentage of organic carbon in a rock
Train	An elongated dispersion pattern stretching downslope or downstream from a source
Vitrinite reflectance (R_o)	The reflectance of vitrinite, used as a measure of thermal maturity

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Standard limits and code classes change between editions. Check the current editions of NIS 554, the WHO guidelines and ACI 318 or BRE SD1 before quoting them in a report.

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