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Quantitative Multi-Attribute Seismic Characterisation of Reservoir Heterogeneity in the RND Field, Offshore Niger Delta, Nigeria

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Abstract

This study evaluates the relative information content of multiple seismic attributes for characterising reservoir heterogeneity in the RND Field, offshore Niger Delta, Nigeria. Building on the previously established structural interpretation, five wells and a three-dimensional post-stack time-migrated seismic volume were integrated within the mapped R1, R2 and R3 reservoir framework. Five attributes—Variance, Relative Acoustic Impedance (RAI), Root Mean Square (RMS) amplitude, Instantaneous Frequency (IF) and Sweetness—were sampled within the interpreted reservoir intervals. Their information content was assessed using analysis of variance (ANOVA), Mutual Information and multicollinearity diagnostics to examine discrimination, nonlinear information and attribute redundancy, respectively. Variance yielded the highest ANOVA F-statistic (7013.50), followed by RAI (692.29), RMS amplitude (652.93), IF (344.76) and Sweetness (51.95). Mutual Information values were 0.502 for Variance, RMS amplitude and Sweetness, 0.371 for RAI and 0.211 for IF, indicating differing but partly complementary information content among the attributes. Variance provided the strongest univariate discrimination, consistent with the faulted and compartmentalised character of the field. RMS amplitude and RAI captured important variations in reflection strength and elastic properties, respectively. Although Sweetness exhibited weaker linear discrimination, it retained substantial nonlinear information. These findings demonstrate that visual expression alone is insufficient for ranking seismic attributes and that their usefulness depends on the geological characteristics of the field. Quantitative evaluation of multiple attributes within an established geological framework therefore provides a more defensible basis for reservoir characterisation than reliance on a single attribute, while highlighting the value of considering both univariate discrimination and nonlinear information when assessing reservoir heterogeneity.

Keywords

Seismic Attributes;
Variance;
Relative Acoustic Impedance;
RMS Amplitude;
Instantaneous Frequency;
Sweetness;
Reservoir Heterogeneity;
Niger Delta.

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1. Introduction

Three-dimensional seismic attributes are widely used to enhance geological features that may be difficult to recognise on conventional amplitude displays. Different attributes respond to different components of the seismic signal and therefore provide different geological information. Discontinuity attributes can enhance faults and abrupt lateral changes, amplitude measures can emphasise reflection-energy variation, impedance-related attributes respond to elastic contrasts, and frequency-based measures may reveal subtle stratigraphic changes. Their interpretation is most reliable when constrained by well information and an independently established geological framework (Avseth *et al.*, 2005; Chopra and Marfurt, 2007; Jegede *et al.*, 2015).

In the Niger Delta, reservoir architecture reflects the combined effects of rapid clastic sedimentation, facies variability and gravity-driven deformation. Alternating sandstone and shale within the Agbada Formation are commonly segmented by growth faults, antithetic structures and associated rollover geometries, producing lateral changes in reservoir continuity and seismic response (Doust and Omatsola, 1990; Evamy *et al.*, 1978; Weber, 1987). These conditions make the basin suitable for multi-attribute analysis, but they also increase the risk of assigning geological meaning to isolated seismic anomalies.

Previous work on the RND Field established its three-dimensional structural framework, including 32 mapped faults, three reservoir horizons and several fault-related closure styles (Owonipa et al., 2026). That structural interpretation provides the geological framework within which the present study evaluates the information carried by five seismic attributes. This distinction is important because the present contribution concerns quantitative attribute behaviour rather than renewed structural mapping.

The objective is therefore to compare Variance, Relative Acoustic Impedance (RAI), Root Mean Square (RMS) amplitude, Instantaneous Frequency (IF) and Sweetness using complementary statistical measures, and to determine what their relative behaviour reveals about reservoir heterogeneity in the RND Field. The emphasis is on attribute ranking, complementarity and geological interpretation rather than on prospect ranking or re-description of the previously published fault framework.

2. Geological Context

The RND Field is situated within the offshore Niger Delta near the Coastal Swamp-Offshore depobelt transition (see Figure 1). The reservoir-bearing succession belongs principally to the Agbada Formation, a paralic sandstone-shale unit developed between the deeper marine Akata Formation and the continental Benin Formation (Doust and Omatsola, 1990; Short and Stauble, 1967; Whiteman, 1982).

The R1, R2 and R3 reservoirs occur within a structurally segmented setting (see Figure 2). The previously established structural model shows growth, antithetic, back-to-back and counter-regional fault relationships that locally modify reservoir geometry and continuity (Owonipa *et al.*, 2026). For the present analysis, this mapped framework is treated as geological control for attribute extraction and interpretation rather than as a new structural result.

An independently established well-log stratigraphic framework also indicates vertically and laterally variable stacking within the reservoir-bearing succession (Owonipa *et al.*, 2026). In this paper that stratigraphic information is used only to prevent attribute responses from being interpreted without depositional context; detailed sequence-stratigraphic subdivision and reservoir-quality comparison are outside the scope of the present contribution.

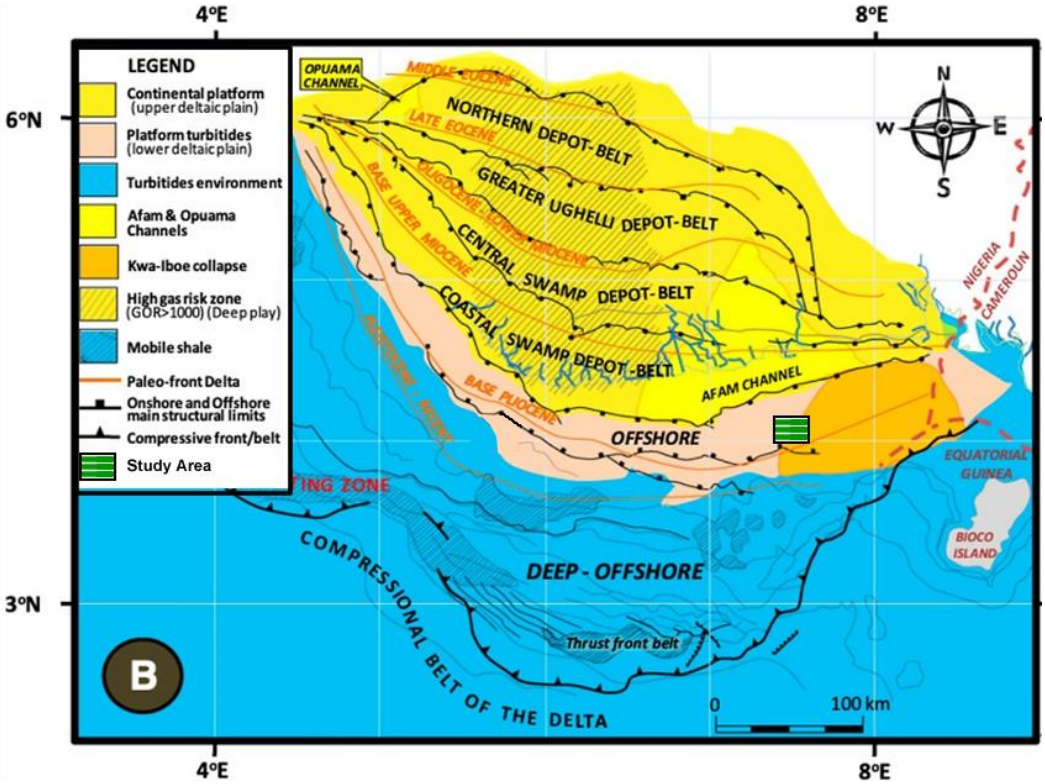


Figure. 1. *Depobelts and principal structural domains of the Niger Delta, showing the study area. [Ebong et al. (2020); Doust H (1990), Owonipa et al., 2026]*

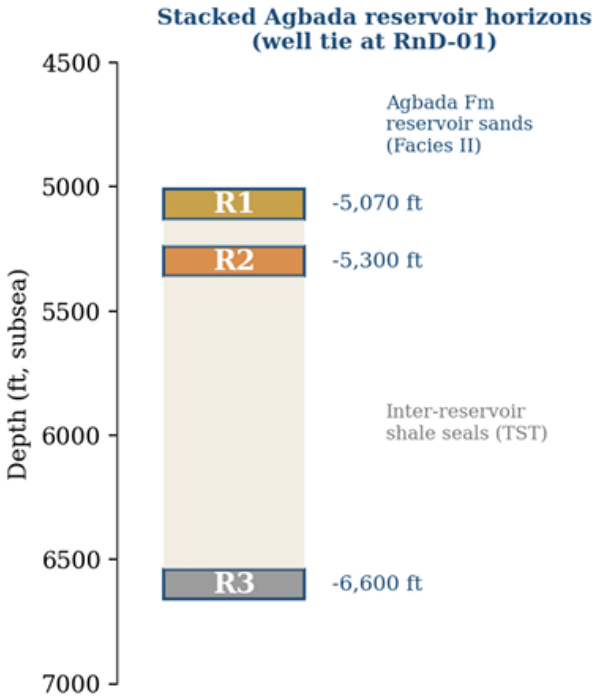


Figure 2: Stacked Agbada reservoir horizons R1, R2, and R3 with inter reservoir shale seals, as tied at the RND-01 well (Owonipa e t al., 2026).

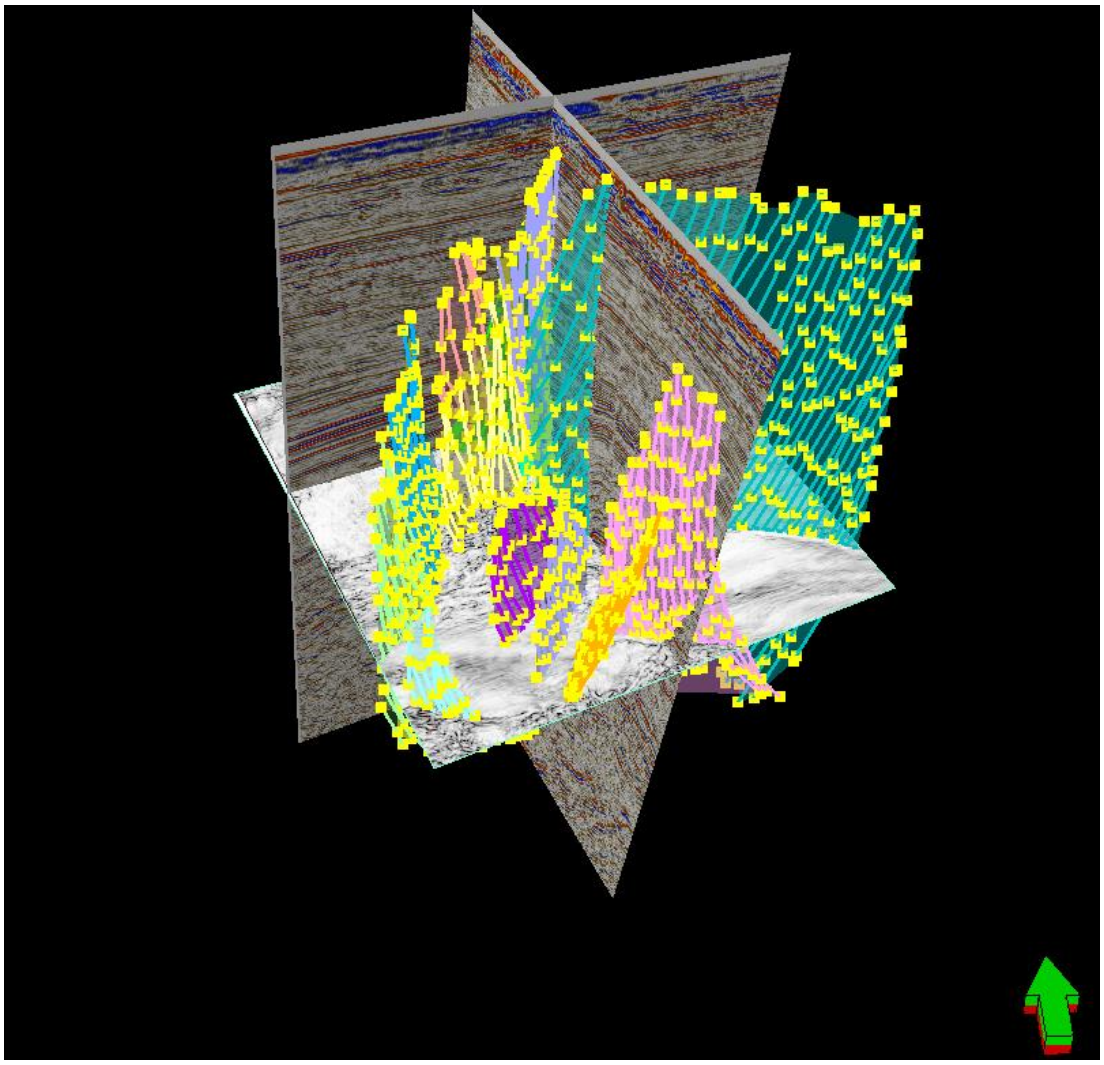


Figure 3. Previously established three-dimensional structural framework of the RND Field used as geological control for the present attribute analysis. (after Owonipa et al., 2026).

3. Materials and Methods

3.1 Data framework

Five wells and a 3D post-stack time-migrated seismic volume were used. Reservoir horizons R1, R2 and R3 had previously been tied to the seismic volume and mapped within the field. Attribute extraction was undertaken only after the reservoir surfaces and structural discontinuities had been established, thereby reducing spatial mismatch between well observations and seismic-derived variables.

3.2 Seismic attributes

The evaluated attributes were Variance, RAI, RMS amplitude, IF and Sweetness. Variance was used to represent lateral discontinuity and reflector incoherence. RAI provided a relative measure of impedance variation. RMS amplitude summarised reflection energy within the selected seismic window. IF described local frequency behaviour, while Sweetness combined amplitude and frequency information. The attributes were sampled at well locations within the mapped reservoir intervals and aligned with the corresponding reservoir observations. RAI, RMS amplitude, IF and Sweetness quantitative responses are presented through the verified statistical results.

3.3 Quantitative evaluation

Three complementary screening measures were considered. ANOVA F-statistics quantified univariate separation associated with each predictor. Mutual Information (MI) assessed broader dependency, including nonlinear relationships that may not be captured by a purely linear or mean-separation statistic. Variance Inflation Factor (VIF) values were retained as a diagnostic of interdependence among predictors. The measures were interpreted together because a high F-statistic does not necessarily imply that an attribute contains all of the information present in another attribute, while high VIF values caution against treating correlated attributes as statistically independent.

4. Results

4.1 Attribute discrimination

The five seismic attributes were all statistically significant in the ANOVA screening, but their discriminatory strengths differed substantially. Variance was dominant, with an F-statistic of 7013.50. RAI and RMS formed a second high-ranking group with F-statistics of 692.29 and 652.93, respectively. IF recorded 344.76, while Sweetness had the lowest F-statistic among the five seismic attributes at 51.95 (see Table 1). The magnitude of the differences shows that the attributes do not contribute equally to differentiation within the integrated reservoir dataset (see Figure 4).

Table 1. Quantitative screening of the principal seismic attributes in the RND Field.

Seismic attribute	ANOVA F-statistic	p-value	Mutual Information
Variance	7013.50044	< 0.001	0.502
RAI	692.29019	8.48×10^{-115}	0.371
RMS amplitude	652.93476	8.31×10^{-110}	0.502
Instantaneous Frequency	344.75654	8.21×10^{-66}	0.211
Sweetness	51.94664	1.17×10^{-12}	0.502

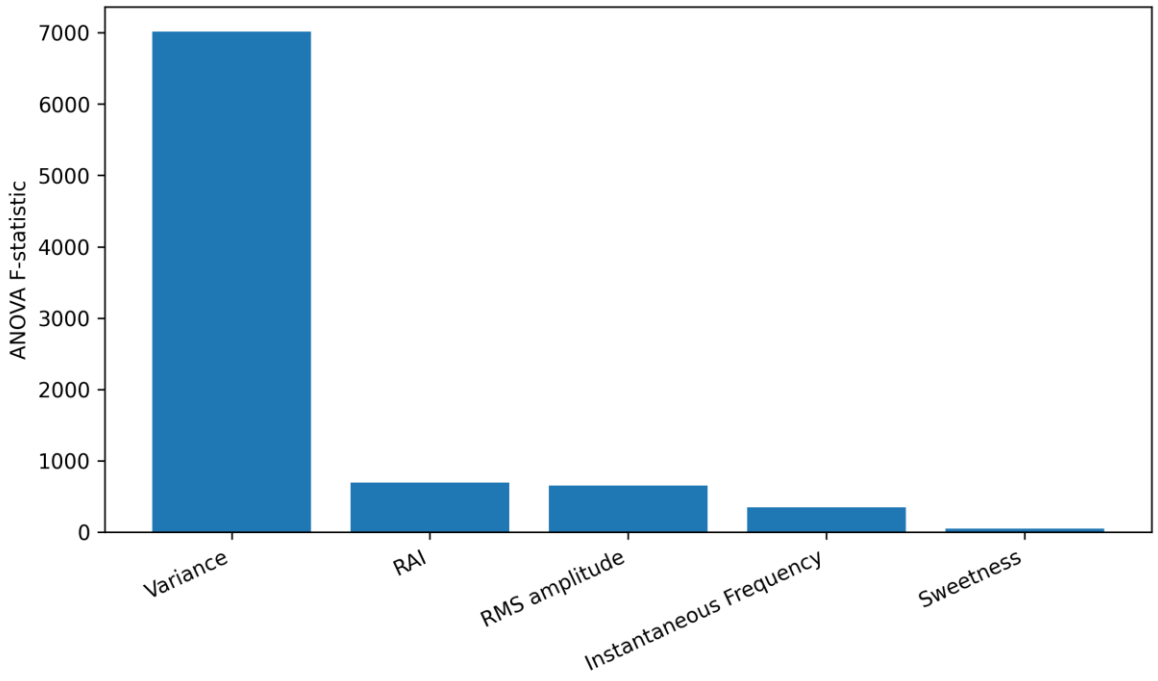


Figure 4. ANOVA F-statistics for the five principal seismic attributes. Variance provides the strongest univariate discrimination in the integrated RND reservoir dataset.

4.2 Complementary information from Mutual Information

The MI results modify the interpretation obtained from ANOVA alone. Variance, RMS and Sweetness each recorded MI = 0.502, RAI recorded 0.371 and IF 0.211 (see Table 1). Sweetness therefore shows an important contrast: it has a much smaller ANOVA F-statistic than Variance, RAI and RMS, yet its MI value is among the highest. This indicates that its relationship with the reservoir dataset is not adequately described by univariate mean separation alone and may contain nonlinear or interaction-related information (see Figure 5)

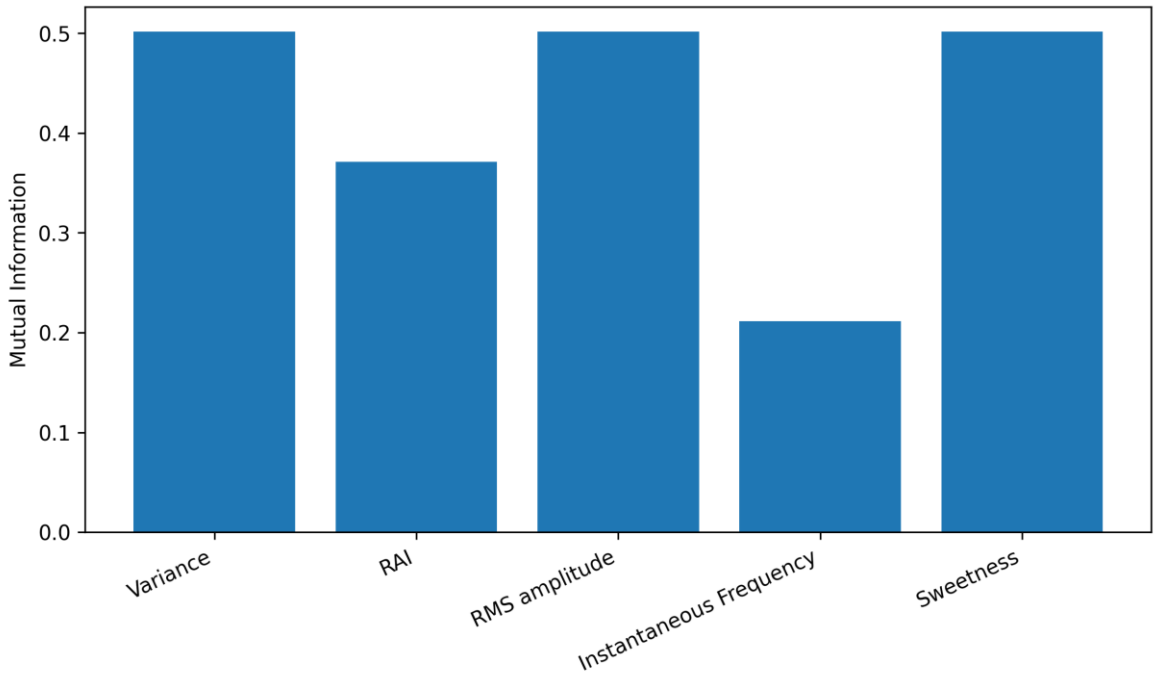


Figure 5. Mutual Information scores for the five principal seismic attributes. The equal MI values of Variance, RMS amplitude and Sweetness contrast with their markedly different ANOVA F-statistics.

4.3 Predictor interdependence

The reported VIF values were high for several variables, including RMS (273.62), Variance (108.37), Sweetness (69.74) and IF (36.26), while RAI recorded a lower but still elevated value of 7.15. These results indicate substantial interdependence among the seismic attributes. Consequently, the attribute rankings should not be interpreted as evidence that each predictor represents an independent geological process. Rather, several attributes respond to related aspects of the same seismic wavefield while retaining different sensitivities to discontinuity, amplitude, impedance and frequency.

Table 2. Variance Inflation Factor diagnostics for the five seismic attributes.

Attribute	**VIF**	**Interpretive implication**
RMS amplitude	273.62	Very high interdependence
Variance	108.37	Very high interdependence
Sweetness	69.74	High interdependence
Instantaneous Frequency	36.26	High interdependence
RAI	7.15	Elevated interdependence

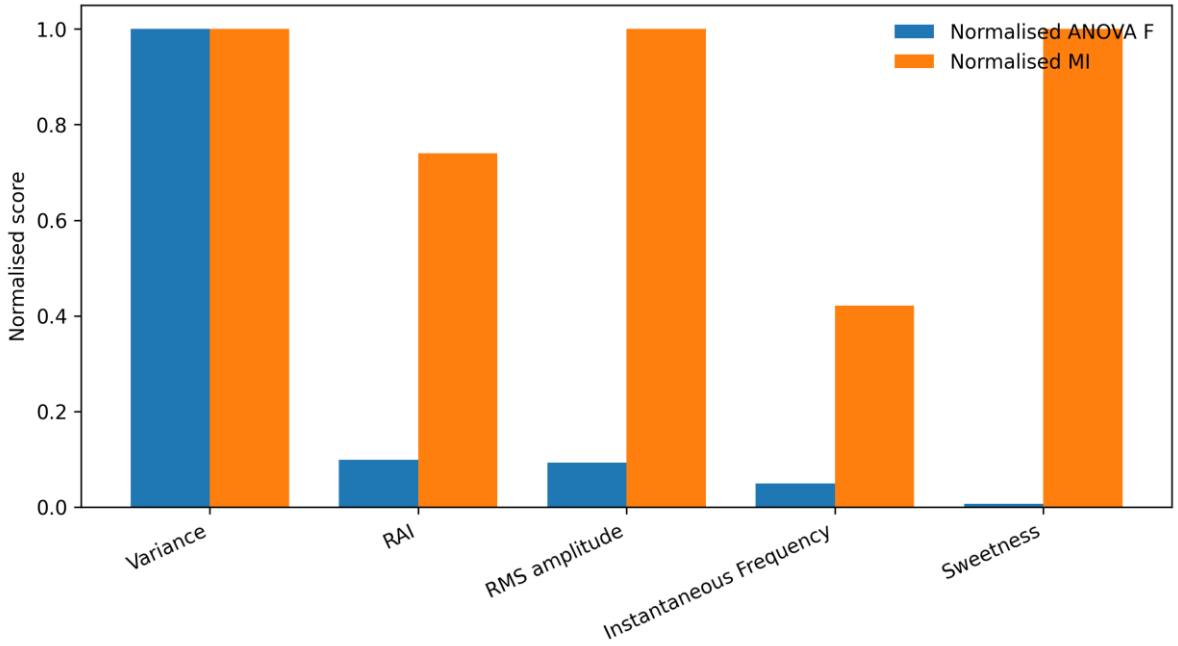


Figure 6. Comparison of normalised ANOVA F-statistics and Mutual Information scores. The divergence for Sweetness illustrates why complementary statistical criteria are required for attribute ranking.

4.4 Geological meaning of the ranked attributes

Variance is the clearest univariate discriminator in the dataset. Its dominance is compatible with the previously mapped faulted framework of the RND Field, because abrupt lateral changes in reflector continuity occur around faults, compartment boundaries and other stratigraphic discontinuities. The result therefore supports the interpretation that lateral discontinuity is a major component of reservoir heterogeneity in the field, without requiring the structural analysis itself to be repeated.

RMS amplitude and RAI also carry strong information. RMS responds to changes in reflection energy, while RAI is sensitive to relative elastic-property contrasts. Their high rankings are consistent with lithological and petrophysical variations within interbedded Agbada sandstone-shale successions (Avseth *et al.*, 2005). IF contributes additional frequency information and may be useful where thin-bed or subtle stratigraphic effects are not fully expressed by amplitude measures.

Sweetness requires a more qualified interpretation. Its comparatively low ANOVA ranking but high MI value shows why attribute evaluation based on one statistic alone may be misleading. Sweetness remains informative, but its contribution appears more nonlinear or conditional than that of Variance. This also demonstrates that an attribute reported as useful in one Niger Delta field should not automatically be assumed to be the strongest discriminator in another (Jegede *et al.*, 2015).

5. Discussion

The principal contribution of this study is the quantitative comparison of multiple seismic attributes within an already established geological framework. This differs from the earlier RND structural study, which focused on fault geometry, seismic facies, closures and prospect configuration (Owonipa et al., 2026). Here, those elements function as geological constraints for understanding why particular attributes respond strongly, rather than as results to be rediscovered.

The very large F-statistic for Variance indicates that discontinuity-related information is especially pronounced in the RND dataset. In a field affected by growth and subsidiary faulting, this is geologically plausible because reflector continuity changes rapidly across structural boundaries. Discontinuity attributes are widely used to enhance faults and stratigraphic edges, but their interpretation remains strongest when checked against mapped seismic geometry rather than treated as stand-alone evidence (Chopra and Marfurt, 2007).

RAI and RMS provide a different but complementary response. Acoustic impedance is controlled by velocity and density, whereas RMS amplitude summarises reflection strength over a window. Their strong statistical behaviour suggests that elastic and amplitude variations remain important after the structural framework has been accounted for. This agrees with the broader principle that reservoir characterisation benefits from combining attributes sensitive to different physical properties rather than depending on a single seismic measure (Avseth *et al.*, 2005; Jegede *et al.*, 2015).

The contrast between ANOVA and MI is particularly important. Sweetness would appear relatively weak if judged only by its F-statistic, but its MI value equals those of Variance and RMS. This indicates that the attribute contains information that may be expressed through nonlinear relationships or interactions. Conversely, the high VIF values show that the attributes are not independent. A high-ranking attribute should therefore be interpreted as informative within the integrated dataset, not as a unique or exclusive geological control.

These findings have a practical implication for seismic-attribute selection. Visual attractiveness or precedent from another field is insufficient justification for choosing an attribute. Attribute selection should combine geological reasoning with quantitative screening, while recognising redundancy and scale dependence. For the RND Field, Variance, RMS and RAI form the strongest core set under the present screening, with IF and Sweetness providing

complementary frequency-related and nonlinear information.

The paper therefore extends the RND research programme. Its specific contribution is to show how multiple seismic attributes behave quantitatively within the established reservoir framework and why their relative usefulness differs.

6. Conclusions

Quantitative evaluation of five seismic attributes shows that their discriminatory behaviour differs markedly within the RND reservoir dataset. Variance has the strongest univariate response, followed by RAI, RMS amplitude, IF and Sweetness.

Mutual Information provides an important complementary perspective. Variance, RMS and Sweetness each recorded MI = 0.502, demonstrating that Sweetness retains substantial information despite its lower ANOVA F-statistic. Attribute ranking is therefore sensitive to the statistical measure used.

High VIF values demonstrate substantial interdependence among several attributes. The seismic predictors should consequently be regarded as complementary but partly redundant descriptions of the seismic wavefield rather than as independent geological controls.

The dominance of Variance is consistent with the established faulted and compartmentalised framework of the RND Field, while RAI and RMS reflect important elastic and reflection-strength variations. IF and Sweetness contribute additional frequency-related and nonlinear information.

The study demonstrates that multi-attribute seismic characterisation is more defensible when attribute selection is quantitatively evaluated and geologically constrained. For the RND Field, this approach provides a distinct contribution beyond the previously published structural interpretation and the separate sequence-stratigraphic analysis.

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