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ORIGINAL PAPER

GRAVITY STRIKE ANGLES TO SEEK CONDITIONS FAVORABLE FOR HYDROCARBON OCCURRENCES IN VENEZUELA

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ABSTRACT

We contribute to the search for hydrocarbon resources with a remote sensing approach. There are traditional terrestrial procedures to seek oil/gas deposits but these are out of scope of this report. Their results, however, are used for independent comparisons. We work with the gravity aspects – functions of the static gravitational potential, namely the gravity strike angles. The gravity aspects are computed from the Stokes parameters (harmonic potential coefficients), characterizing the disturbing gravitational potential, given in the so-called gravity field models (in our case, it is EIGEN 6C4). Our method requires sufficiently large, extensive, and high-density contrast between the material of the studied area and its surroundings. The application for Venezuela is specific because Venezuela has many non-typical high-density heavy oils. We found that our method works also here but the results must be interpreted with caution. The strike angles are often highly aligned/combed in the areas of known oil/gas deposits, like Maracaibo, Gulf of Venezuela, Paraguaná Peninsula, Maturin or Carupano Basin Gas fields. It is more complicated for the Orinoco Heavy Oil Belt. We show zones with highly combed strike angles across all of Venezuela (other than the known ones or those predicted by terrestrial methods); this indicates the presence of possible further hydrocarbon reserves.

1. INTRODUCTION

Venezuela has the world's biggest proven oil reserves (EIA, 2024) and has overtaken Saudi Arabia. Venezuela holds around 90% of proven extra *heavy oil* reserves globally, located dominantly in the Orinoco Belt, La Luna Petroleum system and East Venezuela Basin Province (USGS, Schenk et al. (2023), see figure/slide #3 in the *Supplementary material* SM3, i.e. SM3:3). The enormous oil sands deposits (Orinoco Heavy Oil Belt, OHOB, the USGS report from 2023) are deeply buried; about 380–650 billion barrels (~10^{11} m^3) could be technically recoverable. [Note: the terms billion and trillion follow European usage]. Venezuela has the eighth-largest proven natural gas reserves in the world (ICLG, 2025). The geology of petroleum in Venezuela has already been reviewed by Fary Jr. (1980) and James (2000).

Most of the country's production to ~2000 has come from the Maracaibo Basin (James, 2000, p. 136). The Basin lies within a deformation region created by the interaction of the Caribbean and South American plates; this interaction has contributed to the formation of the extensive oil reserves. The Basin contains lighter oil and gas at depth and heavy oil at shallow depths.

Most of the petroleum industry in Venezuela was developed by foreign investment; it was nationalized in 1975, with multilateral negative impacts, not only economic, but also environmental – for example, at the Maracaibo Lake).

One of the data types used usually to seek for oil/gas reserves and study oil/gas deposits are gravity data, mostly the gravity anomalies (measured by gravimeters), sometimes also the second derivatives of the disturbing potential (measured by gradiometers). The gravity reacts on density variations. To study various geological features, we work with the gravity quantities but with something more powerful than are the gravity anomalies themselves. We make use of a set of gravity (gravitational) aspects (descriptors). They describe the source of density anomalies (causative bodies, target deposits) much better than the traditional gravity anomalies alone (Sect. 2, SM1). We apply the gravity aspects to detect a lower density/higher porosity material and existing subsurface stresses. Such localities have a higher probability of hydrocarbon occurrences, but the task is ambiguous (see more below). We work first of all with the gravity strike angles θ, one of the gravity aspects (Klokočník et al., 2025c and references to older papers therein).

Our approach is independent of traditional terrestrial methods searching for the oil/gas deposits. It is a proxy method in category of remote sensing. No touch, no drilling.

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All the gravity aspects are computed from the gravity field models. These are sets of Stokes parameters (harmonic geopotential coefficients) given in spherical harmonic expansion of the static gravitational potential of the planet in question (here the Earth). They are derived from diverse terrestrial and satellite data types, gathered over a long period of various types of observations, in large volumes (a long-term international effort; results available to everybody). More about theoretical aspects of our method can be found in Sect. 2 and SM1 or in (Klokočník et al. 2017a, 2020a, c).

The strike angles θ (Sect. 2 and SM1) are, in the general case, oriented chaotically, in different directions (azimuths). Sometimes, within a certain area, they are aligned, e.g., linearly along a fault (or near to it) or around the impact crater (creating a halo encircling the feature); we say that they are combed. The combed strike angles indicate regions with lower-density or higher-porosity subsurface material (compared with surrounding rocks) where some tension/force/pressure/stress/motion is present. Such localities bear sediments, groundwater, paleo-lakes, mineral resources, impact craters, subglacial volcanoes, trenches, mountain belts, etc. One reason for the alignment of θ may be hydrocarbon occurrences. It depends on the context.

We have developed an empirical criterion to measure intensity of such an alignment – how much the strike angles θ are combed, the *Comb* factor (Kletetschka et al., 2022; Klokočník et al., 2019; the former in a modified form is used here; Figure *SM1-A1*). The *Comb* factor lies between 0 and 1; for *Comb*=0, θ are not combed, for *Comb*=1, they are perfectly combed.

A relationship between oil/gas deposits and the combed strike angles has been discovered for Ghawar (Saudi Arabia) and the Caspian Sea in (Klokočník and Kostelecký, 2014), by a chance. Later, we extended our studies already intentionally to many localities. The method has been applied for various geological features on the Earth (Klokočník et al., 2014, 2017a-c, 2018, 2020a-c, 2021a), on the Moon (Kletetschka et al., 2022; Klokočník et al.; 2022a, b; 2025b), and on Mars (Klokočník et al., 2023a, b). We have tested large oil/gas fields in Ghawar, Persian Gulf, Mexican Gulf, the Caspian Sea, Ukraine and the Black Sea, West Siberian Basin, Yamal (Russia) or in the Arctic area, e.g., at the submarine Lomonosov Belt (Klokočník and Kostelecký, 2014; Klokočník et al., 2020b, 2021a and review Klokočník et al., 2025a).

In our previous papers, we have documented that gravity aspects provide much more complete information about the subsurface density anomaly than gravity anomalies alone. The individual gravity aspects are sensitive in various ways to the underground lithological density contrasts (variations) and stress field orientation due to the causative bodies (density variations). We recall Figure 2.1 in Klokočník et al. (2017a). The set of the gravity aspects provides information about location, shape, orientation, and the tendency to a 2D or 3D shape of the causative body. It is remarkable that even dynamic phenomena such as stress tendencies and tensions, concerning various geological features, can be imprinted in and expressed by the strike angles, although the input data used to compute the strike angles are always the same – the harmonic coefficients of the static gravity model.

We must be aware that the gravity aspects only indicate geologic structures, any of which may occasionally contain concentrations of the target deposit of various practical minerals, groundwater, ice, permafrost, or hydrocarbons. The combed θ is not directly due to mineral, gas, oil, coal, or water content. They are due to the internal rock anisotropy and existing stresses. Thus, the combed θ only may indicate locations with hydrocarbons or the fact that the hydrocarbons can occur close to the areas with the combed strike angles, but the gravity information alone is not unique (e.g., Klokočník et al.; 2017a; 2020a; 2025c; SM1, SM2, or Oruç et al., 2025). Another look (with virtual deformations) offer Eppelbaum (2017) and Eppelbaum et al. (2018).

Four geologic conditions guide considerations of ultimate reserves and the prospects for finding new areas productive of oil in Venezuela", wrote Fary Jr. (1980). "These are: 1) the highly variable nature, both vertically and horizontally, of the sedimentary facies; 2) the widespread presence of great volumes of oil; 3) the great thicknesses of sediments; and 4) the complicated late Eocene to middle Oligocene folding and faulting..."

Here we test how the strike angles work for Venezuela and the near seas. This was our primary goal; we are aware that we deal with a different situation than normally with the light oil/gas deposits with low density. Our method requires "sufficient" density contrast. This is such a contrast in what generates measurable gravity anomalies and other gravity aspects. Thus, we wish to know whether even such a denser material (dense, heavy "oil", not floating on water) than usually (light oils floating on water) is able to produce measurable density anomalies in terms of the gravity aspects. The answer is positive in general, but it depends on the locality (Sect. 3). On the other hand, many other places than those black spots in SM3:5,6 disclose a higher probability for further possible untapped deposits; they have the strike angles highly combed (Sect. 3 and SM3:14,15,23,24,26-30,36-39,42-50). An analogy and experience tell us that this finding may indicate further deposit sites, not yet known. It cannot be excluded, however, that the combed θ indicates something other than the hydrocarbons, for example, porous sediments alone, salt, paleolake, or groundwater without oil/gas. This is typical, well-known drawback of the gravity data; it alone does not provide a unique solution; research need additional data (from geology, geophysics, seismics, topography, magnetism, archaeology, …). We must be always aware that correlation does not mean causation.

Table. 1 Physical and mathematical significance of the gravity aspects.

Gravity aspects [unit]	***Name*** *reference to formula in Supplement SM1*	***meaning***
Δg [mGal]	gravity anomaly gravity perturbation SM1-A2	traditional quantity used in geodesy and geophysics, radial derivative of the disturbing potential
T_{zz} [E]	radial component of the Marussi tensor SM1-A3	Marussi tensor, tensor of the second derivatives of the disturbing potential
I_1 [s^{-4}]	gravity invariant SM1-A4	one of the gravity invariants
I_2[s^{-6}]	gravity invariant SM1-A5	one of the gravity invariants
I [-]	ratio of the gravity invariants SM1-A6	shape indicator of the causative body
θ [deg]	strike angle SM1-A7	stresses, tensions θ can be the main direction of the Marussi tensor
vd [-]	virtual deformation SM1-A13	dilatation, compression

Section 2 recalls the theory, method, and data. The Supplement SM1 belongs to Sect. 2 and deals with the Theory and physical meaning of the gravity aspects; the reader should start reading with it. Our results for Venezuela are presented in Sect. 3 and SM3, first with a lecture how the combed strike angles work, see Sect. 3.1 and SM2, then with the presentation of our results, see Sect. 3.2 and SM3, and finally comparing our results to others, see Sect. 3.3 and SM3 (Fary Jr., 1980; James, 2000; Schenk et al., 2009), to all attainable results from independent classical prospective methods (Sect. 3.3, SM3: 3-8, 42-50, 52-53).

Our remote sensing method is suitable as one of the pre-drilling tools, without any need for specific drilling. It can be included among known procedures to verify known oil&gas localities or may serve as a preliminary diagnostic tool to find potential oil&gas reserves, untouched by the drilling, yet undeveloped.

The Supplements SM1–SM3 can be downloaded from: https://space.asu.cas.cz/~jklokocn/Venezuela26_Supplementary_materials/ .

2. NOTES TO THEORY, METHOD, AND DATA

We work with the following gravity aspects (reviewed in SM1 and Table 1): *gravity anomalies* Δg (gravity disturbances), SM1:A2, *Marussi tensor* $\mathbf{\Gamma}$ of the second derivatives of the disturbing external static gravitational potential, SM1:A3, namely with its radial component T_{zz}, with the *gravity invariants* I_1 and *I2*, SM1:A4-5 and their specific *ratio I* (SM1:A6, a shape indicator of subsurface density anomaly, variations of a causative body, energy resources, target deposit TD), with *virtual deformations vd*, SM1:A13, and with the *strike angles* θ, SM1:A7 (Kalvoda et al. (2013) and Klokočník et al. (2014)).

We cannot reproduce all about the theory in the main text (selfplagiarism and length of the paper)., Thus, we refer to Pedersen and Rasmussen (1990), Beiki and Pedersen (2010) and to our books Klokočník et al. (2017a, 2020a). The reader should begin his/her reading with our Supplement SM1. Then he should see the examples in SM2 or in Klokočník et al. (2025c).

Here, we repeat the definition of the strike angles θ, because they are the most important in our actual application for Venezuela. Then, we need a comment about the combed strike angles.

Pedersen and Rasmussen (1990) defined the *strike angle* θ as follows:

$$\tan 2\theta = 2\frac{T_{xy}(T_{xx}+T_{yy})+T_{xz}T_{yz}}{T_{xx}^2-T_{yy}^2+T_{xz}^2-T_{yz}^2} \qquad \text{SM1(A7)}$$

where θ is estimated within a multiple of $\pi/2$; and only one value represents the main direction of $\mathbf{\Gamma}$. The quantities T_{ij} are components of $\mathbf{\Gamma}$. Provided that the ratio *I* of the two gravity invariants in (A6) is small, the strike angle may indicate a dominant 2D structure (condition necessary but not sufficient). If one were able to rotate with the structure in such a way that the elements of the first row and first column of $\mathbf{\Gamma}$ were identically equal to zero, then one would reach the direction of "stress fields" (Beiki and Pedersen, 2010).

The input to our analyses is always a set of the Stokes parameters from the gravity field models (SM1:A1). The gravity aspects are the output. They are computed by means of formulae SM1: A2-A13, using software developed by (Bucha and Janák, 2013) and by our own software. The figures are plotted by generic software *Surfer* and by using our additional programs.

Gravity data: We use the combined static gravitational field model *EIGEN 6C4* (*E*uropean *I*mproved *G*ravity model of the *E*arth by *N*ew techniques), Förste et al. (2014), computed from various satellite and terrestrial data. The spherical harmonic expansion of the potential goes in degree and order d/o of the Stokes parameters C_{lm}, S_{lm} to

2190. It corresponds to the ground half-wavelength resolution 5x5' (~9 km on the Earth's surface), see SM1 for the definition and examples.

Topography data: ETOPO 22 update is the globally valid, quality surface (not subglacial) topography models (NOAA, 2022). It is a part of the global 1' relief model of the Earth that integrates land topography and ocean bathymetry from many satellite and other measurements. Its precision in heights is globally ~10 m. It superseded ETOPO 1 (Amante and Eakins, 2009).

3. RESULTS

3.1. LEARNING ABOUT THE COMBED STRIKE ANGLES

We begin with a tutorial lecture SM2 showing "how it works" elsewhere (outside Venezuela) and for various geological features. The reader should (i) be aware of the difference between the combed (aligned) and not-combed (the are "dishelved", chaotic, with various directions) strike angles, Figures *SM1-A1-3*, SM2:6, (ii) should know what it is the *Comb* factor (Sect. 1 and SM1, pp. 8-13, SM2:6) to express a degree of alignment of θ (how much the strike angles are combed), and (iii) should read the theory in SM1 first and also the notes about the physical meaning and interpretation possibilities of the combed strike angles to understand what we are doing here.

The selected tutorial examples for various geological features are gathered to SM2 and shortly commented, always before the sub-series for a specific feature on an extra slide. Finally, SM3 is focused on our results for Venezuela.

Other our papers have also extensive supplements, e.g., Klokočník et al. (2020b, c; 2025c) for the Earth or Klokočník et al (2022a, b) for the Moon, including the *Atlas* of the gravity aspects, and Klokočník et al (2023a, b) for Mars.

3.2. OUR RESULTS FOR VENEZUELA

Figures 1a, b and 2a, b and extensive supplementary set in SM3 show our results for Venezuela. We also reproduce results of others about oil/gas deposits in Venezuela, for a comparison. First, we present the ETOPO 22 shaded topography for Venezuela from Maracaibo Basin on the west going to offshore between Venezuela and Guyana on the east (Fig. 1a, SM3:9) and the strike angles θ for the ratio I<0.9 with the *Comb* factors (Fig. 1b). We can see large lowlands (basins), like Maracaibo with the lake, valley of the Orinoco River, or shallow sea waters. With the threshold I<0.3, intended for flatter density generating sources, we can lose a part of stress information (SM3).

It is useful to have a look at the gravity aspects in a wider surrounding of Venezuela – the Caribbean belt (the Lesser Antilles subduction zone) and the Atlantic Ocean, SM3:11-17, mainly for geologists (commonly they can see only Δg, may be also Tzz). The strike angles are highly combed along the Caribbean belt and this alignment continues along the shelf to Guyana. On territory of Venezuela, θ are also combed, but not so intensively. It will be studied by closer looks in Figures 2a,b and 3c. The red line on some of figures in SM3 delineates the East Venezuela Basin Province according to the USGS 2009 assessment of recoverable heavy oil resources (SM3:3, Schenk et al., 2009). It is only a schematic delimitation.

An enlargement for Maracaibo shows the ETOPO 22 topography and the gravity aspects in SM3:19-24, Figures 2a-d. The highest alignment of the strike angles is observed (Figs. 2c, d) around the Maracaibo basin (M), in Gulf of Venezuela (GV), Paraguaná Peninsula (PP), Falcón (F), then to the east Maturin (M), Orinoco Heavy Oil Belt, (OHOB), Carupano Basin Gas field (CBGF), and continues offshore to Guyana (Fig.1b).

In Sect. 3.3. we present known oil/gas deposits. The reader can extrapolate that our Figures 1b, 2c, d (and many more in SM3) indicate further localities maybe with not yet discovered oil/gas reserves.

3.3. COMPARISON AND NOTES TO INTERPRETATION

USGS and others have provided estimates for the hydrocarbon occurrences around the world (e.g., Schenk et al., 2009; 2017; 2024; Ulmishek, 2003; USGS, 2011, 2024; EIA, 2024). For Venezuela, we have James (2000) and USGS (2009, 2017). We reproduce *figs.1-2* from James (2000) in SM3:5-6 and use them for a comparison.

We compare Figures 2a,c with the ETOPO 22 topography and the strike angles from EIGEN 6C4 to the drilling places (S3:30 and more) following Schenk et al. (2017) and EIA (2024). We found a fair agreement. A more detailed look will be enabled by zooms (Sects. 3.2, 3.3). Moreover, we predict more promising hydrocarbon localities (Sect. 3.3).

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North-east of Maracaibo Basin, there is (i) a lowland with Falcón gas (F) and condensate fields and (ii) a shallow sea with the Paraguaná Peninsula (label P on Fig. 2a). Our Figure 2c confirms highly combed strike angles for both. "… the Perla (gas) field was described a little over a decade ago as the largest natural gas field discovery in Latin America and one of the largest in the world, located in the Gulf of

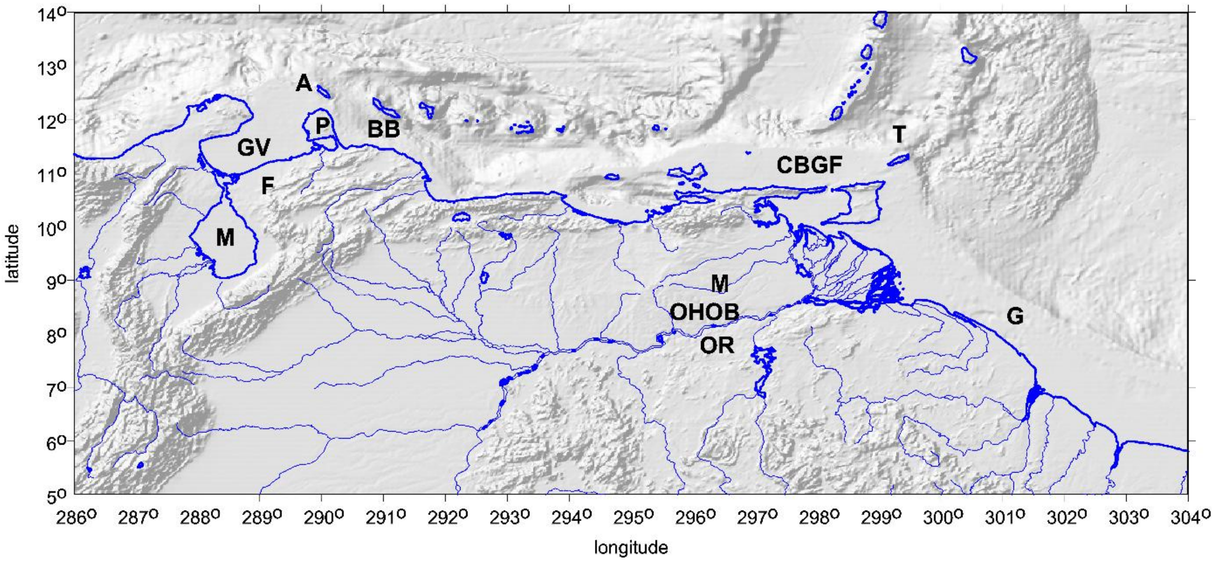


Fig. 1a For the basic orientation. The ETOPO 22 shaded topography for Venezuela. M Maracaibo Basin (Lowlands) with a brackish lake (inlet of the Atlantic Ocean), GV Gulf of Venezuela, A Aruba island, P Para guána Peninsula, F Falcón, BB Bonaire Basin/La Vela Bay, Ma Maturin zone, OHOB Orinoco Heavy Oil Belt, OR Orinoco River, CBGF Carupano Basin Gas field, T Tobago island, G Guyana.

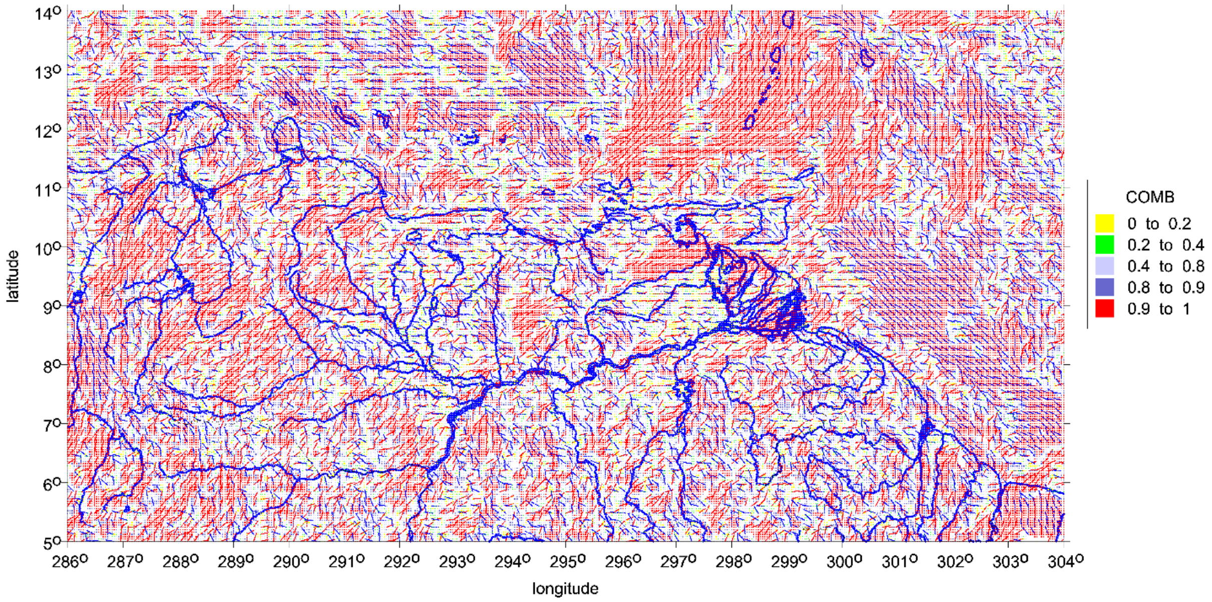


Fig. 1b The strike angles θ [deg] for the ratio I<0.9 and the *Comb* factors for Venezuela computed from EIGEN 6C4 gravity model in the full resolution to degree and order d/o=2190 (the relevant ground resolution is ~9 km), put together into one figure. For further variants of this figure and similar figures see SM3. Red color of θ means the direction to the north from the east and blue color means the direction to the south from the east (see Theory of the strike angles in SM1). The big river (in blue color), W-E oriented, with the delta to the Atlantic Ocean, is the Orinoco River.

Venezuela, 50 kilometers off the coast to the west of the Paraguaná Peninsula…" (ICLG, 2025). This huge gas field contains about 17 trillion cubic feet of gas in situ…" The reader can see there the highly combed θ and the *Comb* factor in Figures 1b, 2c. The older literature cannot contain the information about the Perla gas fields (SM3:3-9). Now we can compare our results in Figures 1b, 2c, d with the localization described above. We observe a good agreement (SM3:24-30).

It is interesting to recall the review Fary Jr. (1980): "… the best prospects for new large oil fields are areas that are wholly or largely under waters in the Gulf of Venezuela, the Gulf de la Vela, and the Cariaco Basins, and in the Orinoco Delta onshore and offshore. These areas were covered by the same seas

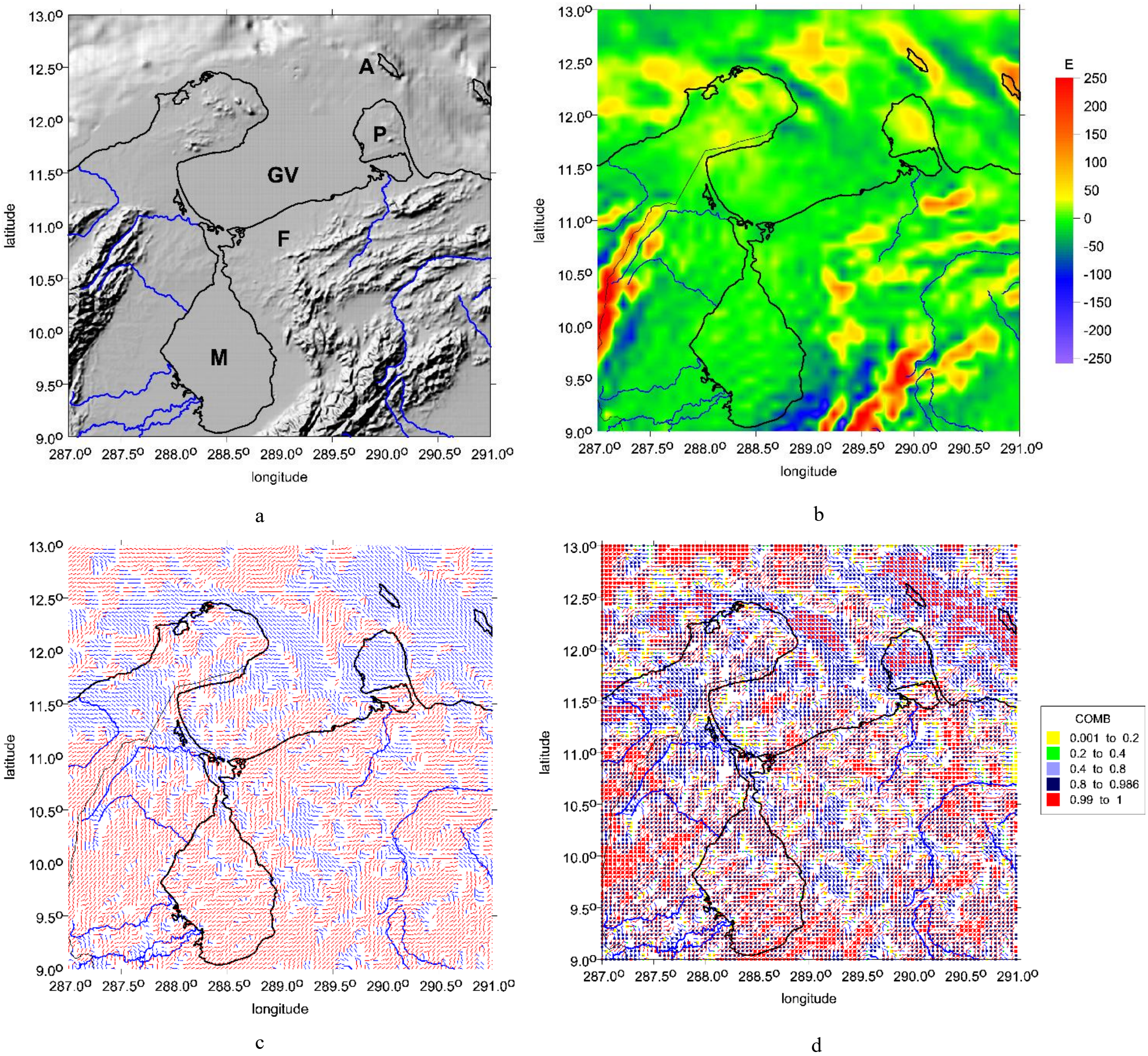


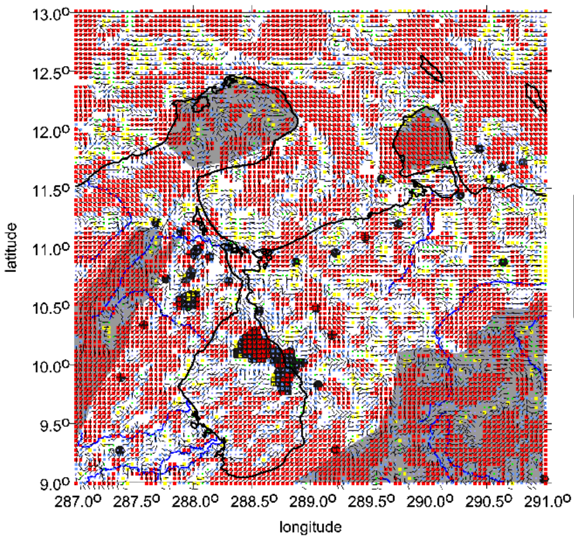
Fig. 2 (a) The ETOPO 22 shaded topography for Maracaibo and Gulf of Venezuela. (b) Second radial derivative T_{zz} [E]. (c) The strike angles θ [deg] for the ratio I<0.9 and (d) the *Comb* factors. For more figures see SM3.

in which the presently producing formations were deposited, and they have remained for the most part untested simply because of the availability of oil in areas that were less expensive to explore and to develop. Discoveries in 1979 of oil in the Gulf de la Vela and of gas 25 miles north of the Peninsula de Paria are very encouraging.“ We can only confirm majority of these older predictions by our recent results, see Figure 3c.

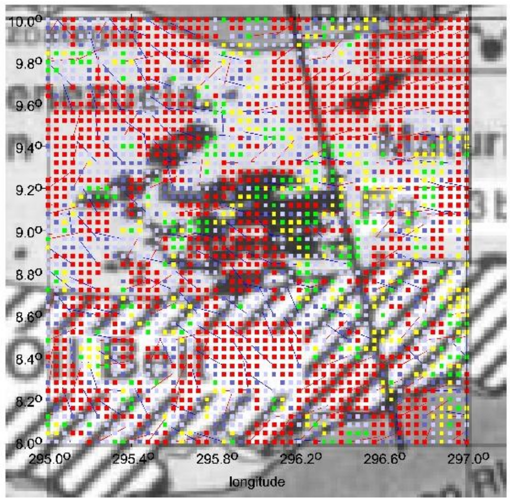
We do not have information about which of the mining sites are currently being mined, already mined or ready or at least planned for mining. We can only speculate indirectly about this from the combined zooms of our images showing θ and the *Comb* factor, such as Figure 1b, figures in SM3, and *fig. 1* with geological formations and the location of the mining sites from James (2000), reproduced here as SM3:3. Such a combined zoom is available for Maracaibo and the Gulf of Venezuela (Fig. 3a) and for the OHOB towards (M) Maturin (Fig. 3b).

Figure 3a documents a good agreement between the deposit locations and the highest *Comb* factors in the Maracaibo Basin and Falcón. The drilling in Gulf of Venezuela and at the Peninsula P is a new or planned; we reveal the highest *Comb* factors there. South-east of the Maracaibo Basin we theoretically predict more deposit sites.

Figure 3b shows a big enlargement of one area north of the OHOB. A partial disagreement between terrestrial results and our remote sensing results (Fig. 3b, S3: 48-50) can be explained by (i) the fact that in OHOB the density contrast is not everywhere large enough to enable our method to work well or (ii) by an oversimplification of the terrestrial resources estimate – blue zone inside the red zone in S3:42.



a



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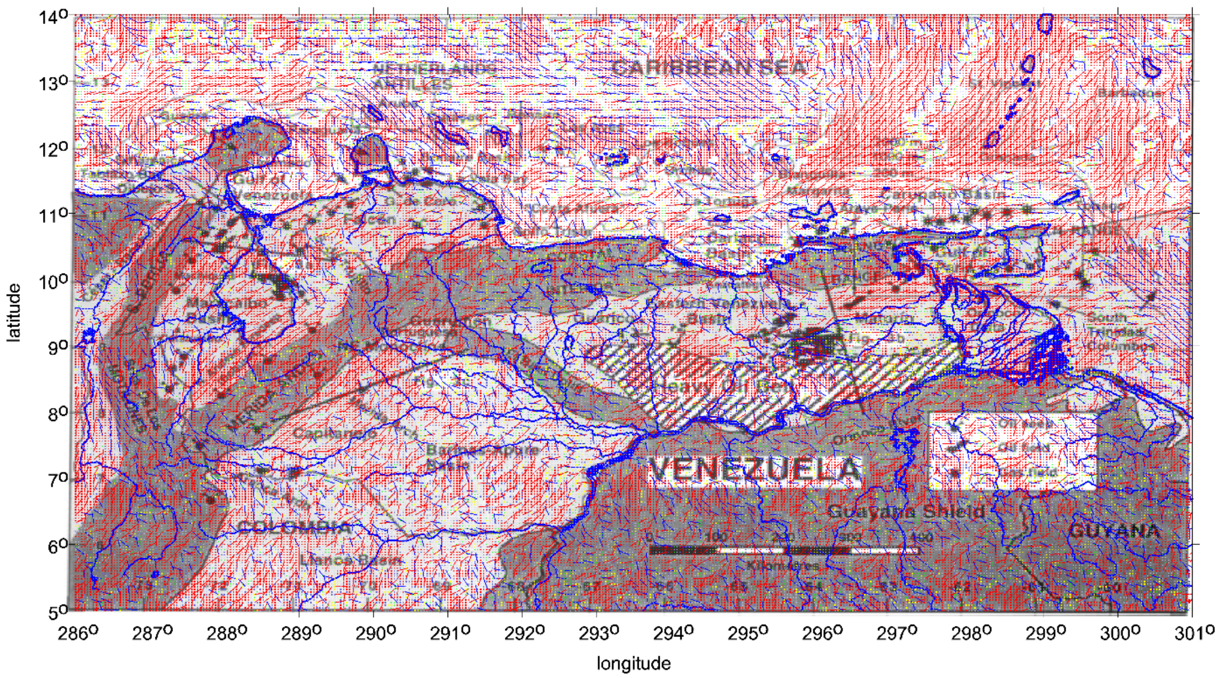

c

Fig. 3 (a), (b): Enlargements from previous figures (a) for Maracaibo and Gulf of Venezuela (west): a composite figure from the *Comb* factors and maps of the active oil/gas deposit sites transformed from maps of James (2000), deep black dots and spots. Zones in grey color are geological features. (b) A close-up of the central and eastern part of Venezuela: a composite figure from the *Comb* factors and maps of the active oil/gas deposit sites from James (2000), with highly variable *Comb*.
(c) Composite figure from the strike angles, the *Comb* factors and the terrestrial-data based maps of the active oil/gas deposit sites from James (2000) for majority of Venezuela. The strike angles θ [deg] are for the ratio $I<0.9$ and the *Comb* factors for Venezuela are computed from EIGEN 6C4 gravity model. Red color of θ means the direction to the north from the east and blue color means the direction to the south from the east.

Another comparison might be feasible – with the independent terrestrial gravity anomalies (not included into EIGEN6C4). We compute a spherical approximation of the gravity perturbations (SM1:A2, SM3:51), but prospectors make use of the Bouguer anomalies (SM3:52, 53) from the measured gravity. This is not mutually comparable. The important argument is that for us, all other gravity aspects, namely the combed strike angles, are more important and more informative than any type of Δg. In Sect. 2 and SM1 we wrote that C_{lm}, S_{lm} to 2190 correspond to the ground half-wavelength resolution 5x5' (~9 km on the Earth's surface). To compare the terrestrial gravity anomalies Δg in 1' step, corresponding to ~2 km on the surface, we would need EIGEN6C4-like model to d/o about 12 000 or to dilute Δg from the terrestrial database about five times. The short-wavelength features, "caught" by the terrestrial anomalies Δg alone, would inevitably be smoothed by their counterpart in the EIGEN6C4 alone. This different "frequency content" is another problem to compare the two sources of Δg.

To compare EIGEN6C4 with terrestrial Δg, we examine the historical review presented by Orihuela (2014). He presented the gravity anomalies over Venezuela. Linares et al. (2015) constructed the maps with terrestrial (traditional) Bouguer anomalies in Venezuela. Their *fig. 7* (here SM3:52) shows Δg_B computed from EIGEN6C4 and *fig. 13* (here SM3:53) shows $\Delta g_{B+EIGEN}$ from the new gravity measurements (that cannot be included in EIGEN6C4), strengthened in a specific way with Δg_B from EIGEN6C4. The short-wavelength features are better described by the latter ($\Delta g_{B+EIGEN}$), as expected. This result (*fig. 13*) is useful for geoapplications. We reproduce their maps as SM3:52, 53 and our gravity perturbations Δg from EIGEN6C4 in SM3:51. As for a comparison, we cannot compare SM3:51 to SM3:52, 53, but we can correlate SM3:53 with the combed strike angles from our computations with the EIGEN 6C4 (Figs. 1b, 2c, SM3:23, 24, 26, 27, 36-39, 44-50). We observe that negative anomalies $\Delta g_{B+EIGEN}$ correlate with highly combed strike angles in the areas: M, GV, F, Ma or CBGF. But both quantities talk about something else, the strike angles θ about stresses, their magnitude and direction.

Note again that the authors of this paper are geodesists and astronomers; their main goal was to test the gravity aspects, namely the strike angles, for the specific situation in Venezuela – occurrences of heavy oils. The interpretation of our results we have to leave on the regional specialists.

4. CONCLUSIONS

We have already studied various geological features on the Earth, the Moon, and Mars by means of gravity aspects (descriptors). It is a typical remote sensing method. The combed (linearly aligned) strike angles θ, one of the gravity aspects derived from the gravity field model EIGEN-6C4 up to maximum d/o=2190, are used to identify localities with conditions favorable for hydrocarbon occurrences in Venezuela. The results achieved are, where possible, compared with known oil/gas reserves and with traditional terrestrial predictions. Very often we state a good agreement. The application to Venezuela is specific because it has predominantly heavy-oil deposits (high-density material), which poses a risk of low-density contrast. We find that our method works also in these conditions but the results must be interpreted with caution. The strike angles are highly combed in such areas of known deposits like the Maracaibo Basin, Gulf of Venezuela, near the Paraguaná Peninsula, Maturin or Carupano Basin Gas fields. It is more complicated for the Orinoco Heavy Oil Belt (Figs. 1a, b, and SM3:38-39, 48-50). The comparison, sometimes with limited ground data, is shown in Figs. 3a, b and in SM3.

Let us recall the axiom that the gravity aspects only indicate geologic structures, any of which may occasionally contain concentrations of the target deposit of various practical minerals, groundwater, ice, permafrost or hydrocarbons, in other words, that the combed strike angles θ are not due directly to minerals, gas, oil, coal or water content (or a combination of previous items). They are due to the internal rock anisotropy and stresses. Thus, we can state that the combed strike angles only indicate locations with hydrocarbons or the fact that the hydrocarbons can occur close to the areas with highly combed strike angles θ.

The study identifies additional areas with the combed strike angles that could signal undiscovered hydrocarbon reserves (Figs. 2 and 3, and series of figures in SM3), while cautioning that gravity data alone cannot uniquely confirm such deposits. They would be located on land of Venezuela as well as in the sea/ocean nearby and would continue to Guyana. Our remote sensing method provides a proxy, diagnostic circumspect prognoses in possible additional petroleum resources.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Jaroslav Klokočník: Writing – review&editing, Writing – original draft, Project administration, Methodology, Investigation, Conceptualization. Jan Kostelecký: Visualization, Software, Investigation, Data curation. Aleš Bezděk: Writing – review& editing, Visualization,Validation, Software, Data curation.

DECLARATION OF COMPETING INTEREST

The authors declare no competing interests. AI was not used in any phase of our research.

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DATA AVAILABILITY

The harmonic geopotential coefficients of the gravity field models and topography models – are publicly available; data of the gravity aspects for our figures and our figures with high resolution (.png files) can be received from Jan Kostelecký on request.

APPENDICES

The Supplements SM1–SM3 can be downloaded from:
https://space.asu.cas.cz/~jklokocn/Venezuela26_Supplementary_materials/

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