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Research Article

Postprocessing of Infrared Reflectography to Support the Study of a Painting: The Case of Vivarini's Polyptych

Laura Fragasso and Nicola Masini

IBAM-CNR (Istituto per i Beni Archeologici e Monumentali), C. da S. Loja, Tito Scalo, 85050 Potenza, Italy

Correspondence should be addressed to L. Fragasso, l.fragasso@ibam.cnr.it

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Infrared (IR) reflectography is an imaging diagnostic technique widely used to study and evaluate the assessment of paintings' conservation state. The study case analyzed in this paper is related to a polyptych panel attributed to Vivarini's workshop conserved in the "Sigismondo Castromediano" Museum in Lecce. The painting's IR reflectography has been acquired through a CCD camera with spectral sensitivity ranging 400–1150 nm and manual positioning system. In order to offset the technological limits of the CCD camera, reflectograms have been processed through Principal Component Analysis and spectral indices. Postprocessing provided information related to the different pictorial drafting and restoration works, as well as emphasized graphic details and shadings, useful to improve the knowledge of the painting techniques.

1. Introduction

As the photoreceptors of the human eye can "see" only in the "visible" spectrum, that is between 380 nm (blue) and 750 nm (red), they are able to detect only the reflected and diffused radiations coming from the most superficial pictorial layers of a painting. If the same photoreceptors were able to detect radiation at greater wave length (>1 μm), they could "see" below the pictorial surface. In fact, the near infrared radiations (with wavelengths ranging from 1 to 3 μm) are able to greatly penetrate the pictorial layer. Part of the radiation is diffused, while the rest is reflected, making it possible to put in evidence what is underdrawings.

Exploiting such a physical characteristic, an imaging diagnostic technique based on near infrared reflectography has been widely employed to study works of art since the sixties [1].

This technique is based on lighting a work of art, in particular a painting, by a source of near infrared radiations. An infrared camera captures the light which reflects off the painting surface. The image captured, that is the infrared reflectogram, is digitized and processed by means of suitable imaging softwares.

The transparency (and reflectance) of a pictorial layer depends on: (i) the optic properties of materials and, therefore, the chemical nature of the pigments, (ii) the thickness of the paint, and the infrared radiation wavelength.

(i) Many paintings are partially or completely transparent while others (i.e., frescoes) absorb the infrared radiations and appear dark. The transparency of the paint layers to the near infrared radiations (with wavelengths ranging from 1 to 2 μm) makes it possible to identify hidden details not visible to the naked eye, such as the underdrawings, changes in the paint layers, and other features behind the pictorial layers [2].

(ii) The longer the infrared wavelength and the thinner the paint layers are, the easier it is to penetrate to the layers beneath.

Since the first studies and applications, lead by Van Asperen De Boer in the sixties [3], NIR reflectography technologies have been strongly increased and improved, especially after the epochal shift from photographical techniques to digital imaging.

The most frequently used technological devises are: (i) camera with Vidicon tube and lead sulfide detector (Pbs), (ii) solid state CCD (Charged Couple Device) camera with silicon detector (CCD-Si), (iii) solid state camera with indium gallium-antimonide (InGaAs) and platinum silicide (PtSi) detectors, and (iv) Infrared scanners [4, 5].

Vidicon cameras acquire images at wavelengths ranging from 0.7 to 2.2 μm, depending on models. Their disadvantages in comparison to more advanced devices are: lower spatial resolution, thermal instability, geometrical distortion.

CCD cameras acquire reflectograms at higher spatial resolution, with better contrast in comparison to Vidicon cameras. However, they have a smaller spectral sensitivity (sp.se.), thus covering the visible spectrum and the near infrared (up to 1 μm). This prevents the sensor from exploring deeper pictorial layers.

Vice versa, solid state cameras with Indium Gallium-Antimonide (InGaAs) and platinum silicide (PtSi) detectors are able to reach deeper layers due to their larger spectral sensitivity, ranging, respectively, from 0.9 to1.7 μm and from 1.2 to 5 μm. Unfortunately, such cameras are very expensive and so their use is restricted to the study of paintings.

In the last twenty years, new devices based on scanning technology have been developed [6]. For example, the INOA IR scanner is a modular device based on an optical head provided with InGaAs photodiode with spectral sensitivity up to 1700 nm and a lighting system which move together on a *x-y* precision translation stage, which makes it possible to take images at very high resolution (16 pixel points for mm^2) without any geometrical distortion [7].

This kind of device has been employed in Italy to map what lays underdrawings and study the painting technique of Pietro Vannucci called "Il Perugino" [8, 9].

Recently, Ambrosini et al. [10] compared such device with a camera provided with an array CCD colour filtered sensor, nominally 350–1100 nm sensitive range, to study "the Virgin with Child" attributed to Cimabue. The underdrawing visibility is improved in the IR Scanner reflectograms thanks to the more extended and uniform spectra sensitivity. However, they are complementary in terms of spectral response to identify several information about the conservation [10].

Gargano et al. [11] compared the performance of different IR reflectographic systems (Vidicon camera, sp.se. up to 2000 nm; solid state Si CCD photocamera, sp.se. up to 1050 nm, 1920 × 2500 pixel; FPA InGaAs camera, sp.se. up to 1700 nm, 320 × 240 pixel; FPA MCT (HgCdTe) camera, sp.se. up to 2500 nm, 320 × 256 pixel; InSb thermocamera, spectr. range 3000–5000 nm, argon cooled) to detect and visualize the underdrawings of paintings.

The comparative study confirmed that the majority pigment's transparency is greater in the 1330–2200 nm range. However, as some pigments are nontransparent in the 0.8–1 μm range, the analyses performed with CCD detector (sp.se. up to 1050 nm) gave immediately preliminary information about these pigments.

For this reason a CCD detector is more effective in detecting restorations and pictorial integrations than wider IR band systems which tend to give very similar responses (reflectance and transparency) for different pigments, unless they use band-pass filters with a 0.8–1 μm range [11].

Figure 1: St. Antonio Abbot attributed to Bartolomeo Vivarini, section of a polyptych dating back to the 15th century, Lecce, Museum "Sigismondo Castromediano": image acquired in the visible spectrum (Panchromatic).

This paper deals with the use of a CCD detector to map hidden features and alterations in a painting on a wooden board by Vivarini, an important Renaissance painter. The instrument limits have been overcome by means of post-processing methods, such as the Principal Component Analysis (PCA) and spectra indices. The choice to adopt such an approach has also been made to enhance possible details in underdrawings and "repentances" not evident observing the non post processed data set.

This paper is organized as follows. Section 2 deals with the potentials of PCA and spectral indices to process IR reflectograms. In Section 3, the study case is described. Section 4 focuses on the experimental section: from acquisition to postprocessing of IR reflectograms. In Section 5, the postprocessing results are described. Conclusions follow in Section 6.

2. Postprocessing of IR Reflectograms by PCA and Spectral Indices: Rational Basis and Study Cases

PCA is a linear transformation which decorrelates multivariate data by translating and/or rotating the axes of the original feature space [12]. In this way, the data can be represented without correlation in a new component space. In order to do this, the process firstly computes the covariance matrix (S) among all input spectral channels, then eigenvalues and eigenvectors of S are calculated in order to obtain the new feature components

$$\operatorname{cov} k_1, k_2 = \frac{1}{m-1} \sum_{i=1} \left(SB_{i,k_1} - \mu_{k_1}\right)\left(SB_{i,k_2} - \mu_{k_2}\right), \quad (1)$$

Figure 2: Visible RGB of Figure 1.

Figure 3: Image acquired with IR2 band with additional information and features (indicated with red and purple color) provided respect to the visible spectrum (RGB and Panchromatic).

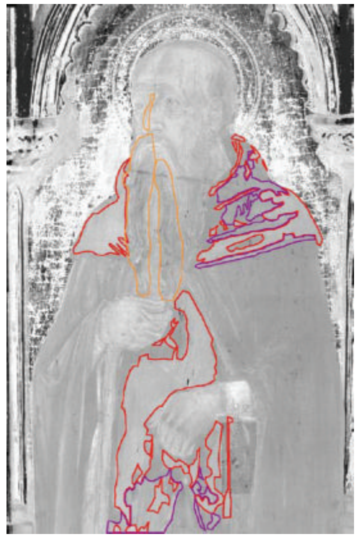


Figure 4: PC2 result with additional information and features provided with respect to the visible spectrum indicated with red and purple colour and to IR2 band, with orange colour, as well.

Figure 5: PC3 result with additional information and features provided with respect to the visible spectrum indicated with red and purple colour and to IR2 band, with green colour, as well.

where k_1, k_2 are two input spectral channels, SB i, j, spectral value of the given channel in row i and column j, n number of row, m number of columns, and μ mean of all pixel SB values in the subscripted input channels.

The percent of total dataset variance explained by each component is obtained by (2)

$$\%i = 100 * \frac{\lambda_i}{\sum_{i=1} \lambda_i}, \tag{2}$$

where λ_i are eigenvalues of S.

Finally, a series of new image layers (called eigenchannels or components) are computed (3) by multiplying, for each pixel, the eigenvector of S for the original value of a given pixel in the input bands

$$P_i = \sum_{i=1} P_k u_{k,i}, \tag{3}$$

where P_i indicates a spectral channel in component i, uk, i eigenvector element for component i in input band k, P_k spectral value for channel k, number of input band.

A loading, or correlation R, of each component i with each input date k can be calculated by using(4)

$$Rk, i = u_{k,i}(\lambda i)^{1/2}(\text{var}_k)^{1/2}, \tag{4}$$

Figure 6: NDI result with additional information and features provided with respect to the visible spectrum (all colours) and to IR2 band, as well (indicated with green, orange and blue colour).

where var k is the variance of input date k (obtained by reading the kth diagonal of the covariance matrix)

So, the PCA transforms the input multispectral bands in new components whose number is equal to (or less than) the input channels.

The PC components are hierarchically ordered, that is, PC1 contains the major variance portion and provides a sort of average of all the input channels, PC2 represents the second maximum variance, and so on.

The major portion of the variance in a multispectral data set is associated with homogeneous areas, whereas localised surface anomalies will be enhanced in later components, which contain less of the total dataset variance. This is the reason why they may represent information variance for a small area or essentially noise, and, in this case, it must be disregarded.

The spectral indices are generally computed by a linear combination of different spectral bands in order to obtain quantitative measures of the surface properties. For environmental studies, spectral indices are used to quantify surface properties such as brightness, moisture, biomass cover, and vegetative vigour. The widest used index is the Normalized Difference Vegetation Index (NDVI) obtained by using the following formula:

$$\text{NDVI} = \frac{(\text{NIR} - \text{RED})}{(\text{NIR} + \text{RED})}. \tag{5}$$

The NDVI operates by contrasting intense chlorophyll pigment absorption in the RED against the high reflectance of leaf mesophyll in the NIR.

PCA and NDVI have been experienced on multispectral satellite images for archaeological purposes [13, 14].

Such methods have been applied for the multispectral imaging of works of art, in particular paintings. By means of PCA, from n-spectral band n-principal components (noncorrelated images) are extrapolated, thus reducing redundancy of the multispectral dataset.

PCA has been applied on images acquired by near-infrared spectroscopic imaging instrumentation, in particular a CCD camera with spectral sensitivity ranging from 650–1040 nm. The images were related to a drawing made by ink and charcoal attributed to Veit Hirschvogel the Elder (1461–1525). A multivariate image analysis produced a set of principal component (PC) images providing a direct visualization of the compositional characteristics of the work of art [15].

A similar PCA case on imaging spectroscopy has been performed by Bacci et al. [16] to investigate the details of drawings by Parmigianino (1503–1540).

PCA has been used by Baronti et al. [17, 18] to analyze different pigments in a painting by Luca Signorelli (well known as “Predella della Trinità”). Different images have been acquired by a Vidicon camera in the visible spectrum (420–750 nm) in the near infrared (750–1550 nm). The visual inspection of PC2 and PC3 in NIR images made it possible to distinguish some areas which, observing the input NIR channel, seemed to be painted with the same pigment.

As for the use of spectral indices, it is possible to mention the application of NDVI to study the fresco “Vergine con Bambino” (Virgin with Child) in the Basilica of St. Peter in Vincoli in Rome [19]. NDVI made it possible to discriminate red pigments in the Virgin’s dress from those in the rest of the painting.

For our study case, a normalized difference index of IR1 and IR2 (NDI = (IR2 − IR1)/(IR2 + IR1)), along with a ratio of the two spectral band (IR1/IR2), have been applied.

3. Study Case

IR reflectography has been experienced on a painting on a wooden board which depicts St. Antonio Abbot (Figure 1). It is part of a polyptych which is considered very important by historical criticism because it witnesses Venetian painting in Apulia (Southern Italy).

The polyptych dates back to the 15th century (post-1463), and it comes from the Church of S. Caterina from Alessandria in Galatina (Lecce, Southern Italy). At present time, it is conserved in the Gallery of Lecce Province Museum “Sigismondo Catromediano.”

It is composed of fourteen distempered panels (total dimensions cm. 215 × 265) depicting on the upper part, from left to right, respectively: St. Caterina from Alessandria, St. Antonio Abbot, St. Nicola from Bari, the Holy Trinity between St. Francesco from Assisi and St. Domenico, St. Ambrogio, St. Girolamo, and St. Agnese.

The panels on the lowest part of the polyptych portray, from left to right, respectively: St. Giovanni Battista, St. Vescovo, St. Paolo, the Virgin in Throne with Child, St. Pietro, St. Benedetto, and St. Michael Archangel.

The polyptych has been restored mainly in the lowest part in 1876 and 1934. It is attributed to the venetian workshop of Vivarini’s family. In particular, the panel which portrays St. Antonio Abbot is attributed to Bartolomeo Vivarini [20, 21].

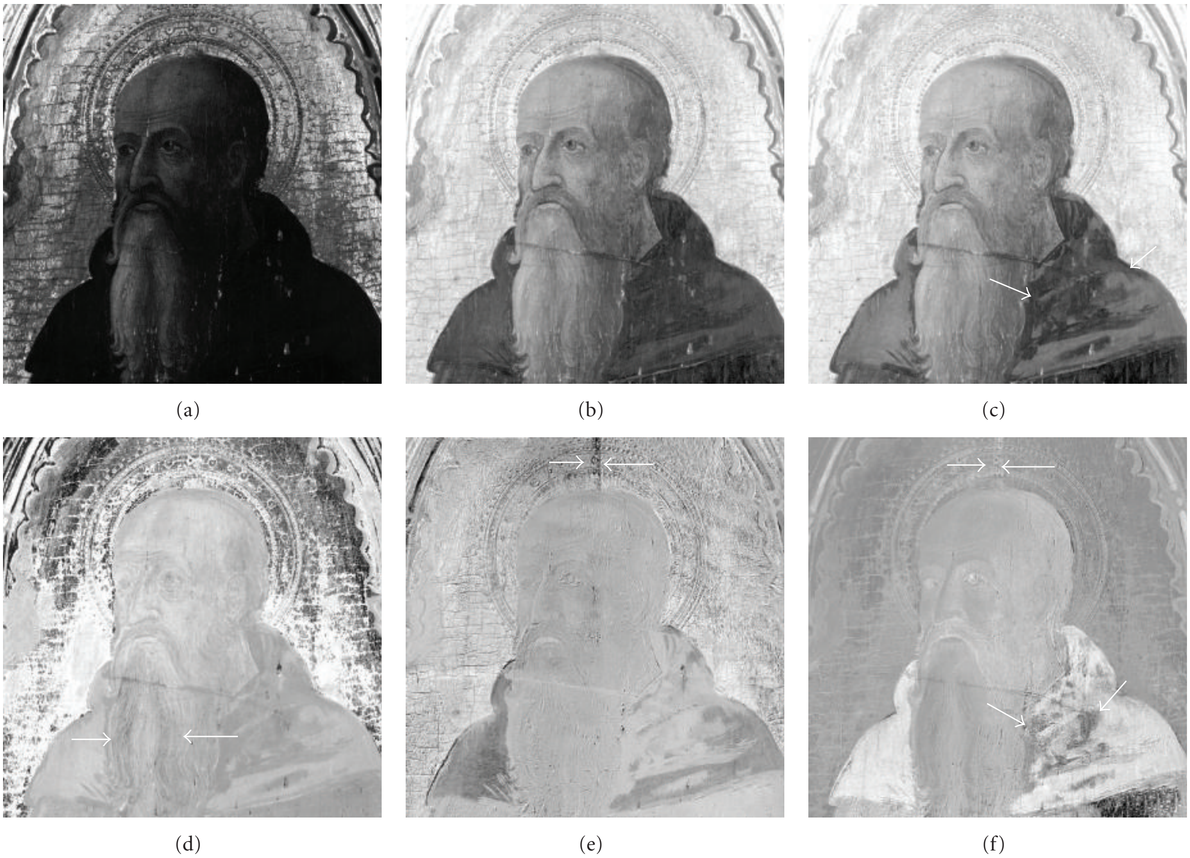
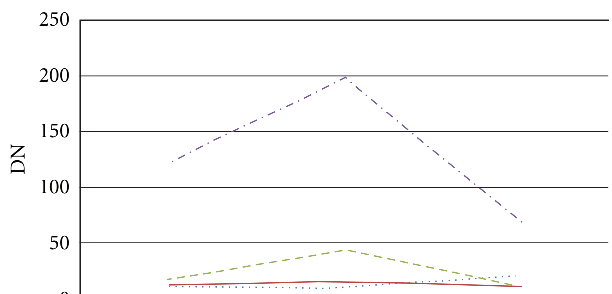


Figure 7: Detail of the upper part of the Saint from PAN (a), IR1 (b), IR2 (c), PC2 (d), PC3 (e), and NDI (f).

Figure 8: RGB image with additional information provided by postprocessing with respect to the data input (see Table 1).



I	II	III
11	10	21
12	16	11
17	44	11
122	198	69

Figure 9: DN average of patterns I, II, and III measured from PAN, IR1, IR2, and NDI.

4. Experimental Section

4.1. Equipment. The IR reflectography of the painting has been acquired by a multispectral imaging system ARTIST, belonging to the Lecce Province Museum “Sigismondo Catromediano.” It consists in a CCD photocamera with spectral sensitivity ranging from 400–1150 nm and manual positioning system.

Table 1: Additional features provided by IR2 with respect to visible, and by PCA and NDI with respect to visible and IR2.

Color	Additional features provided by	With respect to
Red	IR2, PC2, PC3, and NDI	Visible (RGB and PAN)
Purple	IR2, PC2, PC3, and NDI	Visible
Blue	NDI	Visible and IR2
Orange	PC2 and NDI	Visible and IR2
Green	PC3 and NDI	Visible and IR2

The photocamera acquires images in the visible spectrum (panchromatic and RGB, sp.se. 400–700 nm), in the near infrared spectral bands IR1 (sp.se. 700–950 nm), and IR2 (sp.se. 950–1150 nm), at the spatial resolution of 1360×1036 pixel/inch.

The optical head is provided with two lens: one is wide-angle (23 mm focal length) working in F/1.4 configuration, and the other is a zoom (10–108 mm focal length) working in F/2.5 configuration. The lighting system (in the visible and infrared) consists of two 60 W halogen lamps illuminating the painting surface at 45° at the distance of 120 cm.

4.2. Image Acquisition and Processing. The image acquisition and processing consisted in the following steps.

(1) Image acquisition by using the ARTIST software. The picture has been subdivided into a grid of "*n*" rows and "*n*" columns, in order that each acquisition in each band, such as visible panchromatic (PAN), IR1 and IR2, covers an area of 297×214 mm.

(2) Mosaic of the single shots in order to obtain the entire painting image, by using the Panavue Image Assembler 2.06 software, with 20% overlapping.

(3) Georegistration and ortho-rectification of all data set (visible PAN and RGB, IR1, and IR2) by using Global Mapper. This is a crucial step which makes it possible to obtain a precise and orth-rectified overlay of the mosaics over different bands.

(4) First comparative visual inspection of the georegistered and ortho-rectified scenes and first interpretation hypotheses.

(5) Postprocessing of images consisting in filtering, convolution, the application of PCA, and spectral indices using ENVI software.

As for the spectral indices, a Normalized Difference Index (derived from the NDVI)

$$\mathrm{NDI} = \frac{(\mathrm{IR2} - \mathrm{IR1})}{(\mathrm{IR2} + \mathrm{IR1})} \quad (6)$$

has been applied.

The expected results of the above-said postprocessing approach are the enhancement of features and information useful to discriminate pigments.

5. Results

The comparative analysis of the input dataset (PAN, RGB, IR1, and IR2) (see Figures 1–3) have pointed out as follows:

(i) Visible PAN and RGB images highlight the painting conservation state, with a spread phenomenon of crackle and superficial deposits. The painting has undergone different restorations (under the left hand of the Saint there is a protective coat coming from the most recent interventions; see Figures 1 and 2).

(ii) The infrared data, in particular IR2 channel, add further information (see Figure 3) with respect to the scenes acquired in the visible (for such reason and for sake of brevity only IR2 image is showed). As showed in Figure 3, IR2 image reveals on the Saint's tunic and mantle some areas (darker grey) referable to later painting layers, with the classical effect of "leopard spots."

Valuable results have been obtained through PCA and NDI. In detail, the computed principals component have been three, with percentage variance from P1 to Pc3 of 73%, 21%, and 5%, respectively.

(i) The PC1 image summarizes the first maximum variance of the data-set and provides a sort of average of all the input channels. The result is similar to PAN and IR1. This could be due to the fact that the illumination source used has a maximum value of irradiance in the infrared.

(ii) The PC2 (Figure 4) image with respect to PAN puts in evidence the same further information provided by IR2 referable to later intervention of restoration on Saint's tunic and mantle.

(iii) In addition to IR2, PC2 points out brush-strokes to outline the beard and moustaches, as well as to mark some details in the Saint's face (contour of the nose, eyes, expression lines in cheekbones, and forehead, see also Figure 7(d))

(iv) The PC3 image (Figure 5) conserves the additional information of PC2 with respect to PAN related to the mantle and the tunic, but not to the beard of the Saint. Some information of the face disappear. However PC3 put in evidence some more information on decay pathologies and on a discontinuity line in the wooden board on top of the saint halo (contoured by green line in Figure 5; see also Figure 7(e)).

The application of the Normalized index NDI confirms the features observed in PC3 image and provides further data, as well (Figure 6). In particular, the most relevant information provided by NDI is related to the right part of the mantle, contoured by blue line in Figure 6. It is characterized by a nonhomogeneus darker tone which suggests the presence of a restoration work.

As for the filtering, good results have been obtained by directional and high pass, to emphasize the microcracks and fissures which affect the pictorial layer.

Figure 8 shows the RGB image with the features extracted IR2, PCA, and NDI.

As a whole, the comparative observation of data input and the postprocessing results put in evidence that the dark brown mantle and tunic of the Saint has been painted during three phases (I, II, and III, in Figure 8). Figure 9 put in evidence the different discrimination of the patterns I, II, and III in terms of reflectance values (DN values) of IR2 and NDI with respect to the PAN. In particular from PAN and IR1, DN values of the mentioned patterns are similar; whereas from NDI image, DNI values of patterns I, II, and III are very dissimilar.

6. Conclusions

An IR reflectographic system has been used to investigate, in noninvasive way, a spectral region of the visible and near infrared. This is crucial but not exhaustive to characterize the surface and pictorial layers below, due to the limits of the employed sensor (CCD). In order to offset such limits, reflectograms have been processed by PCA and spectral indices (such as NDI).

The analysis has been aimed at focusing some issues of the study case, a polyptych dating back to the 15th century, composed of fourteen panels, among which, for the sake of brevity, only the panel of St. Antonio Abbot has been examined in this paper.

The investigation has been carried on with two aims:

(i) the first is to analyze the stylistic features, since the polyptych is attributed to Vivarini workshop and, in particular, the panel portraying St. Antonio Abbot is thought to be painted by Bartolomeo Vivarini;

(ii) the second aim is to map the restorations which followed each other between the second half of the 19th century and the first half of the 20th century.

The postprocessing methods applied to reflectograms provided additional information with respect to the image input (PAN, IR1 and IR2). A comparative analysis of data input and postprocessing results has been performed by visual observation. Such analysis put in evidence the effectiveness of later principal components (in particular PC3) and the index NDI in discriminating pictorial patterns with the same color (i.e., the dark brown of the mantle and the tunic), thus suggesting different painting phases or restoration works.

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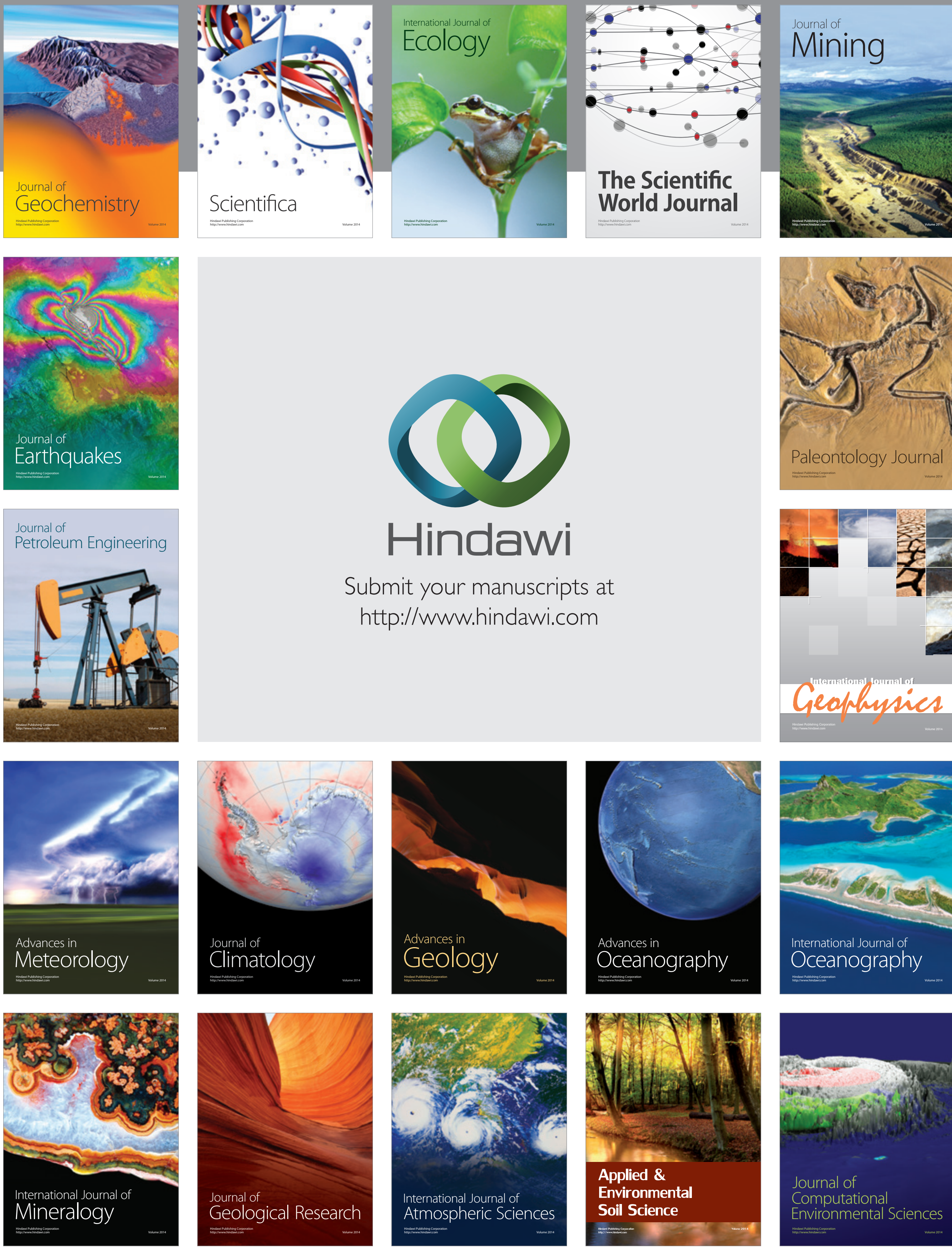
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